Designing Auctions for Renewable Energy Expansion

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Kurzfassung

In dieser Dissertation wird die Ausgestaltung von Auktionen für den Ausbau erneuerbarer Energien untersucht. Einleitend wird ein Überblick über die Ziele des Auktionators, die mit Auktionen für erneuerbare Energien verbundenen Unsicherheiten sowie die entsprechenden Gestaltungsoptionen gegeben. In der Arbeit werden drei Forschungsfragen analysiert, die bisher noch nicht theoretisch untersucht wurden.

Als Erstes werden zwei Konfigurationen von Investitionen in die Informationsbeschaffung zur Eliminierung von Kostenunsicherheit in einer Eingutauktion analysiert: Der Auktionator kann entweder allen Bietern die Informationsbeschaffung vor der Auktion vorschreiben (obligatorische Konfiguration) oder sie dem Auktionsgewinner als eine aufgeschobene Investition nach der Auktion gestatten (freiwillige Konfiguration). Mithilfe eines theoretischen Modells werden fünf Typen symmetrischer Gleichgewichte identifiziert und die beiden Konfigurationen hinsichtlich Teilnahme, Effizienz und erwarteter Gewinne verglichen. Die Analyse zeigt, dass die freiwillige Konfiguration generell von Vorteil ist, insbesondere bei hohen Informationskosten.

Als Zweites werden wettbewerblich allozierte zweiseitige Differenzkontrakte (CfDs) mit Zahlungsauktionen hinsichtlich der Realisierungswahrscheinlichkeit von Projekten verglichen. Dies leistet einen theoretischen Beitrag zur aktuellen politischen Debatte über CfDs. In einem Modell mit unterschiedlichen privaten Kosten und gemeinsamer Unsicherheit hinsichtlich zukünftiger Kosten und Einnahmen zeigt sich: Sind Projekte auch ohne Förderung marktlich realisierbar sind, weisen CfDs unter Risikoneutralität eine geringere Realisierungswahrscheinlichkeit auf als Zahlungsauktionen. Risikoaversion verstärkt dieses Ergebnis. Unter Berücksichtigung asymmetrischer Informationen schlagen wir einen Mechanismus vor, in dem die Projektentwickler (Bieter) wettbewerblich zwischen einem CfD und einer Zahlungsauktion entscheiden. Dabei werden Zahlungsauktionen priorisiert, während CfDs als Rettungsfallschirm bereitgestellt werden, wenn sie für den Ausbau der Windenergie auf See erforderlich sind. Dadurch wird die Realisierungswahrscheinlichkeit erhöht.

Als Drittes werden kombinatorische Auktionen im Kontext erneuerbarer Energien untersucht und deren Potenziale sowie Herausforderungen diskutiert. Kombinatorische Auktionen ermöglichen den Projektentwicklern, komplementäre und substitutive Beziehungen zwischen Projekten in ihre Gebote einzubeziehen, wodurch die Effizienz gefördert wird. Es wird gezeigt, dass das Potenzial kombinatorischer Auktionen für erneuerbare Energien vom Anwendungsbereich abhängt. Zusätzlich werden Implikationen für die Auktionsgestaltung erörtert.

Die Forschungsfragen werden durch politische Diskussionen motiviert. Die für die Analysen verwendeten Modelle abstrahieren von der Komplexität der realen Welt und konzentrieren sich auf die zentralen Entscheidungen im Hinblick auf die Gestaltung des Auktionsdesigns. Die theoretischen Analysen zeigen, wie sich Auktionsdesigns auf Anreize und Ergebnisse auswirken. Daraus werden politische Implikationen abgeleitet.

Diese Arbeit wurde von Herrn Prof. Dr. Karl-Martin Ehrhart am Institut für Volkswirtschaftslehre (ECON) betreut. Sie ist in englischer Sprache verfasst. Dr. rer. pol. ist der angestrebte Doktorgrad.

Abstract

This dissertation investigates the design of auctions for renewable energy expansion. It begins with an overview of the auctioneer's objectives, the uncertainties associated with renewable energy auctions, and the corresponding design choices. The thesis analyzes three research questions that have not yet been examined theoretically.

First, two settings of investment in information acquisition to eliminate cost uncertainty in a single-item procurement auction are analyzed: The auctioneer can either mandate investment in information acquisition before the auction (the mandatory setting) or allow postponed investment by the auction winner after the auction (the voluntary setting). Using a theoretical model, five types of symmetric equilibria are identified, and the two settings are compared in terms of participation, efficiency, and expected profits. The analysis shows that the voluntary setting is generally advantageous over the mandatory setting, especially when information costs are high.

Second, competitively allocated two-sided contracts for difference (CfDs) and payment-only auctions are compared regarding realization probability. This makes a theoretical contribution to the current political debate on CfDs. In a model with different private costs and common uncertainty regarding future costs and revenues, it is shown that if projects are viable without government support, CfDs lead to a lower realization probability than payment-only auctions under risk neutrality. Risk aversion further amplifies this result. Considering asymmetric information, a mechanism is proposed in which developers (bidders) decide competitively between a CfD and a payment-only auction. It prioritizes payment auctions while providing CfDs as a safety net if they are necessary for offshore wind expansion, thereby increasing the realization probability.

Third, combinatorial auctions in the context of renewable energies are studied and their potentials and challenges are discussed. Combinatorial auctions enable project developers to include complementary and substitutive relationships between projects in their bids, thereby promoting efficiency. It is shown that the potentials of combinatorial auctions depend on the area of application. In addition, implications for auction design are discussed.

The research questions are motivated by policy discussions. The models used for the analyses abstract from the complexity of the real world and focus on the key decisions regarding

auction design. The theoretical analyses demonstrate how auction designs affect incentives and outcomes and draw policy implications.

This dissertation was supervised by Prof. Dr. Karl-Martin Ehrhart at the Institute for Economics (ECON) and is written in English. Dr. rer. pol. is the pursued doctoral degree.

Contents

List of figures

List of tables

List of abbreviations

CA combinatorial auction

CfD contract for difference

EU European Union

fCfD financial contract for difference

FIP feed-in premium

FIT feed-in tariff

GVA generalized Vickrey auction

GW gigawatt

kWh kilowatt-hour

LCOE levelized cost of energy

MARI Manually Activated Reserves Initiative

MW megawatt

MWh megawatt-hour

MYR Malaysian ringgit

oFIP one-sided floating feed-in-premium

OREC offshore renewable energy credit

PaB pay-as-bid

PPA Power Purchase Agreement

PV photovoltaic

RE renewable energy

tCfD traditional contract for difference

UK United Kingdom

UP uniform pricing

US United States

VCG Vickrey-Clarke-Groves

List of functions and variables

β_{AB}	package bid in the package bid price format for projects A and B: (P_A, P_B, b)
γ_{AB}	package bid in the component bid price format for projects A and B: $((P_A, b_A), (P_B, b_B))$
γ_A^V	one-project bid for project A in the GVA
γ_A^P	one-project bid for project A in the PaB auction
γ_{AB}^V	package bid in the component bid price format for projects A and B in the GVA
γ_{AB}^P	package bid in the component bid price format for projects A and B in the PaB auction
γ_{AB}^{sV}	package bid in the component bid price format for projects A and B in the GVA, where project B will not be realized in case of winning
γ_{AB}^{sP}	package bid in the component bid price format for projects A and B in the PaB auction, where project B will not be realized in case of winning
γ_m	function of optimal reserve price in the mandatory setting
γ_v	function of optimal reserve price in the voluntary setting
δ	proportion of the payment that is due before the implementation decision
$\Delta\pi_0$	difference in expected profits of the auctioneer between the voluntary and the mandatory setting: $\pi_0^v - \pi_0^m$
$\Delta\pi^v$	difference in expected profits between investors $(\pi^{vi} - c)$ and non-investors (π^{vn}) in the voluntary setting
$\Delta\theta$	difference in private costs between bidders j and i in scenario C: $\theta_j^C - \theta_i^C$
$\Delta\theta^N$	difference in private costs between bidders j and i in scenario N: $\theta_j^N - \theta_i^N$
$\Delta\tau$	difference between parameters τ_h and τ_ℓ
Δq	negligibly small variation in the participation probability q
ΔW	welfare difference between the voluntary and the mandatory setting: $W^v - W^m$
Δz	shift parameter of distribution Z

Δy^*	difference in realization probabilities at the respective award prices between scenarios N and C: $y^*_N(p_N) - y^*_C(p_C)$
θ	private cost signal
θ_i	private cost signal of Bidder i
$\bar{\theta}$	upper limit of private cost interval
$\underline{\theta}$	lower limit of private cost interval
θ_i^C	private costs of Bidder i in scenario C: θ_i
θ_i^N	private costs of Bidder i in scenario N: $\theta_i + \tau_i$
θ_{RAk}	private cost signal of the k-th best risk-averse bidder
θ_{RNk}	private cost signal of the k-th best risk-neutral bidder
$\hat{\theta}_C$	cutoff costs for bidders in scenario C with τ_ℓ or τ_h, representing the value θ at which the corresponding indifference bid equals the maximum bid $\bar{b}_C$: $\hat{\theta}_C = \hat{\theta}_{C,\ell} = \hat{\theta}_{C,h}$
$\hat{\theta}_{N,\ell}$	cutoff costs for bidders in scenario N with τ_ℓ, representing the value θ at which the corresponding indifference bid equals the maximum bid $\bar{b}_N$
$\hat{\theta}_{N,h}$	cutoff costs for bidders in scenario N with τ_h, representing the value θ at which the corresponding indifference bid equals the maximum bid $\bar{b}_N$
Θ	random variable of private cost signals
$\Theta_{(k)}$	random variable of k-th lowest private cost signal
Θ^N	random variable of private costs in scenario N: $\Theta + \mathcal{T}$
$\Theta^N_{(k)}$	random variable of k-th lowest private costs in scenario N
$\overline{\kappa}$	upper limit of the random variable K
$\underline{\kappa}$	lower limit of the random variable K
λ	Lagrange-multiplicand
μ_i	Karush-Kuhn-Tucker (KKT) multipliers associated with the optimization problem
π^m	expected payoff of each participant in the mandatory setting, before subtracting the sunk investment cost c
π^{vi}	expected profit of each investor in the voluntary setting
π^{vn}	expected profit of each non-investors in the voluntary setting
$\pi(s, n)$	expected payoff of a firm with private costs s facing n competitors
π_0^m	expected profit of the auctioneer in the mandatory setting
π_0^v	expected profit of the auctioneer in the voluntary setting
$\pi(\gamma_A^P)$	total profit of a developer who submits bid γ and wins in the auction
Π^V	expected annualized profit of a developer in the GVA
Π^P	expected annualized profit of a developer in the PaB auction
ϱ	probability that a bidder has τ_h
σ	parameter of the mean-preserving contraction that links F_K to F

τ	difference in private costs of the same bidder between scenarios N and C
τ_i	value of τ of Bidder i
τ_h	high value of τ
τ_ℓ	low value of τ
a	developer's project comparison factor: e_A/e_B
$\hat{a}$	auctioneer's project comparison factor: $\hat{q}_A/\hat{q}_B$
$\bar{b}$	maximum bid price
$\underline{b}$	minimum bid price
b_w	weighted average bid price from the developer's view
b_A^P	bid on project A in the component bid price format in the PaB auction
b_B^P	bid on project B in the component bid price format in the PaB auction
b_A^V	bid on project A in the component bid price format in the GVA
b_B^V	bid on project B in the component bid price format in the GVA
b^P	optimal package bid in the package bid price format in the PaB auction
b^V	optimal package bid in the package bid price format in the GVA
$\hat{b}(\gamma_{AB})$	weighted average of the bid prices of γ_{AB} from the auctioneer's view
b_C^*	bidder's indifference bid in scenario C
$b_{C,i}^*$	indifference bid of Bidder i in scenario C
b_N^*	bidder's indifference bid in scenario N
$b_{N,i}^*$	indifference bid of Bidder i in scenario N
$\bar{b}_C$	upper limit of the bid in scenario C
$\bar{b}_N$	upper limit of the bid in scenario N
b_C^{RA}	indifference bid of a risk-averse bidder in scenario C
b_C^{RN}	indifference bid of a risk-neutral bidder in scenario C
b_C^{RS}	indifference bid of a risk-seeking bidder in scenario C
b_N^{RA}	indifference bid of a risk-averse bidder in scenario N
b_N^{RN}	indifference bid of a risk-neutral bidder in scenario N
b_N^{RS}	indifference bid of a risk-seeking bidder in scenario N
c	investment cost in information acquisition
c_A	annualized costs per energy unit [ct/kWh] of project A
c_B	annualized costs per energy unit [ct/kWh] of project B
$c_{max}(r)$	the highest value of c for which an equilibrium with participation exists
$c_{min}^m(r)$	the lowest value of c such that a slight increase in c would prevent full participation and investment in the mandatory setting
$c_{min}^v(r)$	the lowest value of c such that a slight increase in c would prevent full participation and investment in the voluntary setting
e_A	annual full load hours [h/a] of project A
e_B	annual full load hours [h/a] of project B

CE_X	certainty equivalent of random variable X
E_0	equilibrium without participation
E_1^f	equilibrium with full participation and investment
E_1^r	equilibrium with randomized participation and investment
E_2	equilibrium with full or randomized participation without investment
E_{mix}	equilibrium with mixed investment behavior
$EU_C(b_C^*)$	expected utility of a bidder submitting b_C^* in scenario C
$EU_N(b_N^*)$	expected utility of a bidder submitting b_N^* in scenario N
f	density function of private costs
$f_{(k,n)}$	density function of the k-th lowest of n private cost signals
f_C	density function of F_C
f_N	density function of F_N
F	distribution function of private costs X in Chapter 2 or Θ in Chapter 3
$F_{(k,n)}$	distribution function of the k-th lowest of n private cost signals
F_C	distribution function of the best bid of the other $n-1$ bidders in scenario C
F_K	distribution function of the random variable K, mean-preserving contraction of F
F_N	distribution function of the best bid of the other $n-1$ bidders in scenario N
$1-F_C(b_C^*)$	winning probability of the bidder with indifference bid b_C^* in scenario C
$1-F_C(b_N^*)$	winning probability of the bidder with indifference bid b_N^* in scenario N
g	density function of cost uncertainty Y
G	distribution function of cost uncertainty Y
$G(y_C^*(p_C))$	realization probability in scenario C as a function of the threshold $y_C^*(p_C)$
$G(y_N^*(p_N))$	realization probability in scenario N as a function of the threshold $y_N^*(p_N)$
h	density function of future revenue Z
h_1	density function of updated future revenue Z_1 at the time of the implementation decision
$\hat{h}(b)$	density function of the developer's beliefs about winning with b in the PaB auction
H	distribution function of future revenue Z
H_1	distribution function of updated future revenue Z_1 at the time of the implementation decision
$\hat{H}(b)$	distribution function of the developer's beliefs about winning with b in the PaB auction
K	random variable on the support $[\underline{\kappa}, \overline{\kappa}]$
$L(\cdot)$	Lagrange function

n	number of (other) participants as an auxiliary variable (Chapter 2); number of a priori symmetric bidder (Chapter 3)
n_1	number of investors
n_2	number of non-investors
N	number of potential bidders in the procurement auction
p_C	award price in scenario C
p_N	award price in scenario N
p_N^b	award price in scenario N with a part of the payment due before the implementation decision
P_A	installed (peak) power [MW] of project A
P_B	installed (peak) power [MW] of project B
P_C	random variable of the award price in scenario C
P_N	random variable of the award price in scenario N
$P(n, q)$	probability that exactly n of the $N-1$ other firms participate, each with independent participation probability q
$P_A(n, q)$	probability that exactly n of all N firms participate, each with independent participation probability q
$P(n_1, n_2, q_1, q_2)$	probability that exactly n_1 investors and n_2 non-investors of $n-1$ other firms participate, with the probability of participation with investment q_1 and the probability of participation without investment q_2
$P_A(n_1, n_2, q_1, q_2)$	probability that exactly n_1 investors and n_2 non-investors of all n firms participate, with the probability of participation with investment q_1 and the probability of participation without investment q_2
q	probability of participation with investment in the equilibrium E_1^f
q'	probability of participation without investment in the equilibrium E_2
q_1	probability of participation with investment in the equilibrium E_{mix}
q_2	probability of participation without investment in the equilibrium E_{mix}
$\hat{q}_j$	conversion factor of the auctioneer for project j
r	reserve price
r^*	optimal reserve price
$r_m^*(x_0)$	globally optimal reserve price in the mandatory setting, as a function of the auctioneer's maximum willingness to pay x_0
$r_v^*(x_0)$	globally optimal reserve price in the voluntary setting, as a function of the auctioneer's maximum willingness to pay x_0
s	penalty in case of non-realization
T	length of CfD support (years)
$\mathcal{T}$	random variable of τ

u	von Neumann-Morgenstern utility function
u^{RA}	von Neumann-Morgenstern utility function of the risk-averse bidders
u^{RN}	von Neumann-Morgenstern utility function of the risk-neutral bidders
u^{RS}	von Neumann-Morgenstern utility function of the risk-seeking bidders
$U_C(p_C)$	expected utility conditional on winning at prices p_C in scenario C
$U_N(p_N)$	expected utility conditional on winning at prices p_N in scenario N
w	initial wealth of the bidders
W^m	expected Welfare in the mandatory setting
W^v	expected Welfare in the voluntary setting
W_A	estimated annual energy generation [MWh/a] of project A by the developer
W_B	estimated annual energy generation [MWh/a] of project B by the developer
x	private cost
x_i	private cost of firm i
$\bar{x}$	upper limit of private cost interval
$\underline{x}$	lower limit of private cost interval
x_0	auctioneer's maximum willingness to pay, the value of the fulfilled procurement to the auctioneer
X_i	random variable of the private cost
y	implementation cost
$\bar{y}$	upper limit of cost uncertainty
$\underline{y}$	lower limit of cost uncertainty
$y^*_C(p_C)$	threshold of the implementation cost Y, at which the bidder is indifferent as to whether or not to implement the project in scenario C, as a function of the award price p_C
$y^*_{C_i}(p_C)$	implementation cost threshold of Bidder i in scenario C
$y^{RA}_C(p_C)$	implementation cost threshold of a risk-averse bidder in scenario C
$y^{RN}_C(p_C)$	implementation cost threshold of a risk-neutral bidder in scenario C
$y^{RS}_C(p_C)$	implementation cost threshold of a risk-seeking bidder in scenario C
$y^*_N(p_N)$	threshold of the implementation cost Y, at which the bidder is indifferent as to whether or not to implement the project in scenario N, as a function of the award price p_N
$y^*_{N_i}(p_N)$	implementation cost threshold of Bidder i in scenario N
$y^{RA}_N(p_N)$	implementation cost threshold of a risk-averse bidder in scenario N
$y^{RN}_N(p_N)$	implementation cost threshold of a risk-neutral bidder in scenario N
$y^{RS}_N(p_N)$	implementation cost threshold of a risk-seeking bidder in scenario N

$\hat{y}^*_N$	threshold of the updated implementation cost Y at the time of the implementation decision, at which the bidder is indifferent as to whether or not to implement the project in scenario N
Y	random variable of the cost uncertainty in the implementation cost
z	future revenue
$\bar{z}$	upper limit of future revenue
$\underline{z}$	lower limit of future revenue
Z	random variable of the future revenue
Z_1	random variable of the updated future revenue at the time of the implementation decision

Chapter 1

Introduction

In pursuit of climate-neutrality, major economies are rapidly scaling up renewable power. The United States (US), for example, has pledged to achieve 100% clean electricity by 2035 (US, 2021). Similarly, the European Union (EU)'s revised Renewable Energy Directive 2023 raises the EU-level binding renewable energy (RE) target for 2030 to at least 42.5%, up from 24.5% in 2023, while many member states set even higher targets for renewable electricity (Commission, 2023a; European Environment Agency, 2025; Ember, 2025). Translating such ambitions into reality requires the rapid and reliable expansion of wind, solar, and other RE generation. To support this expansion, policy makers have adapted auctions as the main competitive allocation mechanism for RE projects. For example, EU member states are obliged to implement competitive mechanisms, i.e., auctions, to determine the support for RE (Commission, 2014; European Parliament and Council, 2018a; Commission, 2020).

Auctions are a flexible policy instrument that can be adapted to specific needs and situations, provided that policy makers have a deep understanding of their objectives and how to translate the objectives into effective design elements (Liñeiro and Müsgens, 2023). In fact, auctions have become a common means of promoting RE expansion worldwide. By 2021, 131 countries had implemented RE auctions, and their use continues to expand globally (REN21, 2022; REN21, 2024). del Río and Kiefer (2023) confirm that auctions are the most rapidly expanding form to allocate support for RE deployment. A European Commission analysis notes that national auctions "have allowed Member States to determine the level of financial support for RE technologies in a competitive manner" (Commission, 2024).

Against this background, this thesis offers theoretical analyses of RE auctions. The remainder of the introduction provides the necessary foundations. It defines auctions and their conditions of use, outlines the auctioneer's objectives and the uncertainties faced by bidders and the auctioneer. To address these objectives and uncertainties, different auction design choices are presented. It then reviews the literature on RE auctions and concludes with the approach and research questions studied this thesis.

1.1 Definition and conditions for the use of auctions

McAfee and McMillan (1987a) define an auction as "a market institution with an explicit set of rules determining resource allocation and prices on the basis of bids from the market participants." In principle, auctions are a market institution that coordinates supply and demand. In an auction, there is a single auctioneer who designs and organizes the auction and multiple (potential) bidders who submit bids.[1] In the RE context, the auctioneer is referred to as the representative of the policy makers and the (potential) bidders are developers of RE projects.[2] The exact rules for conducting auctions are determined and published by the auctioneer before the auction and cannot be changed during the auction. The auctioneer and the bidders must commit to these rules, which presents particular challenges for the bidders in the RE context, since the risk of project non-realization may prevent the transaction from being completed.

Auctions can be classified as either forward auctions or reverse auctions according to the direction of money and goods flows. In a forward auction, the auctioneer (seller) offers the auctioned item(s) to bidders (buyers), and the winning bidder(s) makes a payment to the auctioneer. In a reverse auction, the auctioneer (buyer) procures item(s) or service(s) from bidders (sellers) and makes a payment to the winning bidder(s). In the industrial purchasing contexts, reverse auctions are also called procurement auctions. Auctions are won by the bidders with the best bids for the auctioneer. In forward auctions, these are usually the bidders with the highest bids, whereas in reverse auctions, these are the bidders with the lowest bids.[3] In practice, both forward and reverse auctions appear in energy markets; for example, auctions for wind rights at a designated site are forward auctions, while auctions that award support or subsidies are reverse auctions (see examples and discussions in Section 3.6 and Section 4.2.3).

For auctions to work effectively, certain conditions must be met (e.g., Klemperer, 1999). These conditions include (i) The auctioned items should be non-commodities, i.e., not standardized commodities traded in well-established markets such as those sold in stores, but rather specialized goods for which there is not yet a market. (ii) There is asymmetric information about the value of the items, i.e., the bidders typically know the value to themselves more precisely than the auctioneer and the competing bidders. (iii) There is competition among bidders, so not all bidders can win in the auction.

[1]In this thesis, we focus on one-sided auctions, where only one side (the bidders) actively bid, while the other side (the auctioneer) does not. By contrast, two-sided auctions (also called double auctions) involve active bidding from both sides, i.e., both buyers and sellers submit bids and offers simultaneously (McAfee and McMillan, 1987a).

[2]Throughout the thesis, the terms auctioneer and policy maker are used interchangeably.

[3]One exceptional case is the use of discriminatory measures, which can violate this principle by favoring or disfavoring certain bidders or groups of bidders, and by treating their bids differently from other bidders (Kreiss et al., 2021).

The first two conditions are clearly met in the RE sector. Each wind or solar project is unique in location, technology and network context, therefore non-commodities. Bidders in RE auctions participate with their planned installations, which are specifically designed for a particular application. Bidders calculate and estimate the value of these installations as accurately as possible for themselves, or at least have an incentive to do so, but may still face uncertainty regarding future revenue or costs (see Section 1.3). Since these calculations usually require a high degree of internal information and specific knowledge, the information about them is asymmetric between the bidders and the auctioneer. Finally, auctions only work properly if there is competition among bidders, which forces them to base their bids on their estimated valuations. Without competition, bidders will instead base their bids on other factors, such as minimum or maximum prices, in order to optimize their own outcomes. In that case, the items are not sold or procured at competitive prices. As a result, the auction fails to elicit information about bidders' valuations, because bidders cannot be distinguished by their bids. For instance, Titl (2025) states that around 42% of public procurement contracts in Europe are awarded to a sole bidder, implying insufficient competition.

1.2 Auctioneer's objectives

When designing an auction, it is crucial for the auctioneer, i.e., the policy maker in the RE context, to have clear objectives. The most commonly cited objectives include efficiency (welfare maximization), cost minimization in reverse auctions (or profit maximization in forward auctions), and achieving the targeted RE expansion goals (Ehrhart et al., 2020).

One primary auctioneer objective is efficiency (e.g., Krishna, 2010, Ch.1), which is especially important in the context of allocation of subsidies and rights by the public sector (see Chapter 4). Because the term "efficiency" is used in different ways, it needs a precise definition in the RE context. From the general society's viewpoint, efficiency requires production and allocation of goods to be associated with the maximum possible social welfare and is therefore also referred to as allocative efficiency (e.g., Mankiw, 2011, Ch. 1). In the RE context, an efficient outcome refers to achieving a given RE target at the lowest total cost to society (del Río et al., 2015b), i.e., maximizing total surplus conditional on all available information (Dasgupta and Maskin, 2000). Therefore, developers with the lowest costs or developers who assign the highest value to the auctioned items should win. Efficiency is mandated for RE auctions in the EU (European Parliament and Council, 2018b; Commission, 2021). It is also reflected in national or regional laws, for instance in Germany (e.g., BMU, 2016; Bundestag, 2017; Kazakh Government, 2009), California (US), and Mexico (Kreiss et al., 2021; IRENA, 2013).

Closely related is the objective of cost minimization in reverse auctions, i.e., minimizing support payments. For RE subsidies, this directly concerns the auctioneer's financial cost and is often a binding legal requirement. For example, EU state-aid rules state that the aid amount should be “limited to the minimum needed to incentivise the additional investment or activity in the area concerned” (Commission, 2014, §27e). Minimization of support payments is also stipulated, e.g., in Germany, the Netherlands, and the United Kingdom (UK), and is proposed for developing countries (Ehrhart et al., 2020). In forward auctions, the objective is maximizing the auctioneer’s profit or revenue. While profit maximization is generally not emphasized by public policy makers, it is a central objective in classic auction-theoretic literature (e.g., Myerson, 1981; Krishna, 2010). Designing an auction to maximize the expected profit of the auctioneer is known as the optimal auction design, with reserve prices commonly used as instruments (Myerson, 1981).

Another key objective is achieving the targeted expansion of RE, which is explicitly stated, e.g., in Germany, Kazakhstan, Brazil, Mexico, and is proposed for developing countries (Bundestag, 2017; Kazakh Government, 2009; Hochberg and Poudineh, 2018; IRENA, 2013). Reaching expansion targets requires both the successful allocation of the volume put out to tender in the RE auctions and the timely realization of the awarded projects. In practice, both conditions are nontrivial. Several recent offshore-wind auctions attracted no bids at all (Memija, 2024; Crown Estate, 2025; BNetzA, 2025b). Moreover, unlike in classical auction-theoretic literature where outcomes are assumed to be committed (e.g., Krishna, 2010; Milgrom, 2004), real-world auctions face non-realization risk when bidders withdraw or fail to implement awarded projects. Recent examples include Mitsubishi Corporation’s withdrawal from an offshore wind project in Japan (Renewable Energy Institute, 2025), an 18% non-realization rate in German photovoltaic (PV) auctions (Liñeiro and Müsgens, 2021), and concerns about the realization probability of Germany’s offshore-wind awarded projects in 2023 (Ehrhart et al., 2024b). These cases have made project realization a central policy concern. EU policy now explicitly stresses that auction design must “ensure full completion of the projects in a timely manner” (Commission, 2024). It is further stated that, in order to ensure a high project realization rate, it is “particularly important that such auctions are properly designed”(Commission, 2024). In practice, this means including design elements such as prequalification and penalties. Different auction formats and design elements have different effects on the realization probability of awarded project. The question of designing RE auctions with the goal of a high realization probability is explicitly studied in Chapter 3.

Beside the three core objectives discussed above, auctions can serve additional objectives. One is information revelation: Well-designed auctions can elicit bidders’ private cost information, thereby reducing information rents and improving allocative efficiency (Krishna, 2010). Another objective is to foster “dynamic efficiency”. Although this term is not uniformly defined, it refers to improvements in the effectiveness of allocation and production over time (Ghemawat and Costa, 1993; Aydogan, 2023). For RE, dynamic efficiency means that the system should promote competition, create incentives for innovation, and thereby lead to cost reductions and welfare gains in the long run (del Río et al., 2015a). Auctions can also contribute to energy system reliability (Peter and Wagner, 2021) and consumer benefits, i.e., the maximization of the consumer surplus or low prices for the customers (e.g., BMU, 2016; IRENA, 2013; Hochberg and Poudineh, 2018; Kreiss et al., 2021). In addition, auction designs can promote actor diversity by encouraging participation by smaller or community developers (e.g., Bekirsky et al., 2020; Coté et al., 2022) and foster technological diversity to support a mix of technologies (Peter and Wagner, 2021).

In reality, the auctioneer often has multiple objectives, which may conflict if not clearly prioritized (Kreiss et al., 2021; Anatolitis et al., 2025). Since different objectives require different choices of auction formats and design elements, conflicting objectives cannot be achieved simultaneously. For instance, Commission (2014) and Bundestag (2017) stipulate the minimization of support payments and the minimization of overall costs to achieve the RE expansion targets, without prioritizing between them. del Río and Kiefer (2023) summarize examples of trade-offs between different objectives in auctions. As Anatolitis et al. (2025) note, well-designed auctions can efficiently expand RE, but poorly designed ones can lead to unintended outcomes, such as non-participation or inefficient allocation – for instance, when the bidder with the highest willingness to pay does not win. Therefore, a clear and prioritized objective is essential to guide the auction design.

1.3 Uncertainties in auctions

Both the bidders and the auctioneer face significant uncertainty in RE auctions. Bidders often face uncertainty regarding future costs of realizing awarded contracts and regarding future revenue generated by the project (Kreiss et al., 2017b; Schlecht et al., 2024). For example, a wind farm developer does not know its exact preparation, construction, or financing cost until detailed engineering and financing are arranged; besides, revenues depend mainly on future electricity prices and future weather conditions. These uncertainties are to a large extent commonly faced by all bidders but are unknown at the time of the auction. Measures to mitigate cost uncertainty, referred to as investment in information acquisition in this thesis, are costly. Requiring participants to make investments before the auction as project preparation imposes sunk costs, which can reduce participation and impose welfare loss. Alternatively, if bidders can defer the investment until after winning the bid (a more “voluntary” approach), they risk underestimating cost, while the auctioneer faces non-realization risk. In either case, (potential) bidders factor these uncertainties into their participation and bidding decisions (see Chapter 2). To mitigate uncertain future revenue, bidders can be secured by subsidies or hedging instruments offered by the auctioneer, or by bilateral Power Purchase Agreement (PPA) contracts (see Chapter 3).

On the other side, the auctioneer is uncertain about bidders’ valuations of the auctioned items, since each bidder has private cost information that the auctioneer does not know (e.g., Krishna, 2010, Ch.1). The auctioneer may have beliefs (e.g., based on historical cost data) but such information is always imperfect and subject to change, especially when technology costs evolve rapidly. The auctioneer's uncertainty is reinforced by dynamic changes of individual technical parameters and costs as RE auctions are also designed to promote innovation (e.g., del Río et al., 2015b). In practice, it could also be challenging for the auctioneer to assess market conditions in advance and to determine whether bidders need subsidies or support (see Section 3.6.1 for examples). In addition, costs can vary largely among bidders and differ in their structure: Some bidders have economies of scale, others do not, or even have diseconomies of scale due to budget or resource constraints (see Chapter 4 for examples). Typically, the auctioneer lacks detailed information, also because bidders (project developers) withhold information about their cost structures (Bichler et al., 2020).

Despite the uncertainties faced by bidders and the auctioneer, a well-designed auction can still allocate items in line with the auctioneer's objectives, which is a key reason auctions are used. Different auction formats and design elements could be used to address the auctioneer's uncertainties (see Section 1.4, Chapter 3, and Chapter 4). Identifying potential value or cost structures in quantitative terms can help design RE auctions, but knowing them exactly is not necessary. This is because a good auction design should not rely on having extensive information in advance; rather, auctions themselves should reveal the relevant information. To address bidders' uncertainties, the auctioneer can require or offer measures such as prequalification or hedging instruments that help bidders reduce uncertainty. While situations of uncertainty generally favors the use of auctions, successful implementation of auctions depends on several factors, particularly the selection of an appropriate auction design.

1.4 Auction design choices

The key auction design choices considered in this thesis can be grouped into three categories: auctioned item, auction format, and further design elements. For each category, we briefly introduce the relevant design choices, outline their main variants and features. Table 1.1 provides a structured overview and links each design choice to the chapter where it is addressed.

The first category is the auctioned item, i.e., what is being auctioned, which determines both the flow direction of money and good and the auction volume. In RE auctions, the auctioned item can be very different (Gephart et al., 2017; AURES II, 2022). For example, it may be a relatively well-defined item, such as a wind right that gives the owner the right to construct and operate a RE plant at a specified site (Ausubel and Cramton, 2011; Ehrhart et al., 2024a). In such cases, bidders compete either in forward auctions, where their bids express their willingness to pay for the right to implement the project, or in reverse auctions, where they bid for the level of support needed to implement the project.

Table 1.1: Overview of key auction design choices

Category	**Design choice**	**Variants / Features**	**Chapter**
Auctioned item	Flow direction	Forward	3, 4
		Reserve	2, 3, 4
		Either direction	3
	Auction volume	Energy	4
		Capacity	4
		Budget	4
Auction Format	Number of items	Single-item	2, 3
		Multi-item	4
	Bidding structure (in multi-item auctions)	Combinatorial	4
		Simultaneous	4
		Sequential	4
	Award criterion	Price-only	2, 3, 4
		Multi-criteria	-
	Implementation format	Static	2, 3, 4
		Dynamic	-
	Pricing rule	Pay-as-Bid (single- or multi-item)	4
		Second-price (single-item)	2, 3
		Uniform-price (multi-item)	-
		Vickrey (multi-item)	4
Further design elements	Reserve price	General reserve price	2, 3, 4
		Efficient reserve price	2
		Optimal reserve price	2
	Prequalification and penalties	Physical prequalification measures	2
		Financial prequalification measures	-
		Penalty	2, 4
	Support and hedging instruments	Capex support	3, 4
		Opex support: FIT, FIP, CfD	3, 4

The auctioned item can also be characterized by an auction volume, which specifies the total quantity to be procured or allocated. In the RE context, commonly used units of auction volume include capacity (in megawatt (MW)), energy (in megawatt-hour (MWh)), or a budget (in euros) (AURES II, 2022). Auctions that select among multiple individual projects require an additional quantity parameter, namely the project size, which must be expressed in the same unit as the auction volume. This is typical for onshore RE auctions, which are mostly conducted as multi-item auctions (see next paragraph) and allow a single bidder to win multiple projects. In these auctions, the auctioneer specifies a predetermined auction volume, such as the total capacity in MW for one or more technologies. In a reverse auction, bidders then submit for each individual project a bid that includes both a requested support level (e.g., in euros per MWh) and the project size (e.g. the plant's peak capacity in MW). Bids are ranked by support level (lowest first) and awarded until the total auction volume is filled by the awarded projects. Analogously, when energy or budget serves as the auction volume, the same principle applies: Project size corresponds to the expected produced energy or the expected financing requirements of the individual project. A detailed discussion on the auctioned item is provided in Chapter 4.

The second category of design choices concerns the auction format. The first design choice is the number of auctioned items. Auctions can be designed as single-item auctions or multi-item auctions. Although most RE auctions are multi-item auctions (as in Chapter 4; see e.g., del Río and Kiefer (2021)), single-item auctions are discussed in Chapter 2 and Chapter 3, because single-item auctions can illustrate essential auction-relevant effects and are representative for offshore wind auctions. In multi-item auctions, the auctioneer must additionally decide on the bidding structure. One option is to implement a combinatorial auction, in which each bidder can submit bids for single items and package bids for combinations of items (see Chapter 4). If package bids are not allowed (non-combinatorial), the auctioneer should determine whether items are allocated sequentially or simultaneously. A comparison of combinatorial auctions and sequential or simultaneous non-combinatorial auctions is provided in Section 4.4.1.

Another design choice of the auction format is the award criterion. Auctions can be conducted as price-only auctions, where awards depend solely on bid prices, or as multi-criteria auctions, where non-price criteria (i.e., additional factors such as quality level) are considered. A further choice relates to the implementation format: static sealed-bid or dynamic. In a static sealed-bid auction, all bidders submit their bids simultaneously (or within the same time interval) without being aware of competitors' bids; on the contrary, a dynamic auction involves bidders in a dynamic process where the price of the auctioned good changes until the final transaction takes place. In this thesis, the focus is on price-only auctions and on static sealed-bid format, while some static sealed-bid auctions can be implemented alternatively as dynamic auctions.

In addition, the pricing rule decides how award prices are determined. In pay-as-bid (PaB) auctions, each winning bidder pays (or receives) its own bid. In uniform pricing (UP) auctions, all winners pay (or receive) the same clearing price, typically set by the marginal bid. In Vickrey auctions, winners pay (or receive) the lowest (highest) bid with which they could still have secured their allocation, given competitors' offers (Krishna, 2010; Milgrom, 2004). For single-item auctions, both the UP and Vickrey rules reduce to the second-price rule, under which the winner pays (or receives) the second-highest (second-lowest) bid in forward (reverse) settings (e.g., McAfee and McMillan, 1987a).

The third category of design choices comprises of reserve prices, prequalification and penalties, and support and hedging instruments, which are covered in this thesis. Reserve prices are one of the central design elements and are widely applied in RE auctions (IRENA and CEM, 2015; Anatolitis et al., 2022). Reserve prices set binding constraints on bids: In forward auctions they act as lower bounds (minimum bid prices or price floors); in reverse auctions they serve as upper bounds (maximum bid prices, price caps, or ceiling prices). From an auction-theoretic perspective, reserve prices play an essential role in mechanism design (Myerson, 1981; Riley and Samuelson, 1981; Börgers, 2015). If efficiency is the primary objective, the reserve price should be equal to the auctioneer's valuation of the auctioned item (namely the efficient reserve price, see Chapter 2). By contrast, if auctioneer's objective is to maximize expected revenue in forward auctions (or minimize expected procurement costs in reverse auctions), the optimal reserve price is generally above (below) the auctioneer's valuation (Myerson (1981), see Chapter 2 for examples). Since such reserve prices exclude potential bidders whose valuations lie between the reserve price and the auctioneer's valuation, allocative efficiency is no longer guaranteed. In RE context, in reverse auctions for financial support, the main function of maximum bid prices is to prevent excessive bids (del Río and Kiefer (2017), see also Chapter 3). Maximum bid prices are also used to signal the auctioneer's maximum willingness to pay, which relates to the targeted expansion of RE and the assessment and intensification of technical and competitive developments in the RE markets (Hanke and Tiedemann, 2020). Reserve prices can also be used to effectively mitigate the risk of tacit collusion and distorted incentives of strategic bidding (Burkett and Woodward, 2020, see also Section 4.4.2).

When bidders facing uncertainties (see Section 1.3), prequalification and penalties are measures to enhance the effectiveness of RE auctions by ensuring credible bids, to promote timely project implementation, and to reduce non-realization risk (del Río and Linares, 2014; AURES II, 2022). Prequalification requirements can be physical or financial. Physical prequalification requires bidders to undertake certain preparatory efforts prior to the auction, such as obtaining permits and expert opinions, concrete project plans, or arranging financing commitments. These upfront efforts entail sunk costs for bidders (Menezes and Monteiro, 2000; Tan and Yilankaya, 2006). Physical prequalification measures are popular in RE auctions because they force bidders to take a closer look at the planned project and its implementation before the auction, thus reducing bidders' uncertainty in this regard, which leads to more precise bids and, above all, a lower non-realization risk (Kreiss et al. (2017a), see also Chapter 2). Financial prequalification measures include deposits, such as bid bonds, that participants must post prior to the auction. The deposits will be refunded if obligations are met but partially or fully forfeited in cases of non-compliance. Penalties are imposed in the same way as how deposit repayments decrease when projects fail to be realized (del Río and Linares, 2014). Penalties affect both bidding behavior and implementation probability. First, high penalty leads to less aggressive bids. Second, after the auction, a rational auction winner would track potential losses due to increased project costs, which is only tolerated up to the penalty amount; otherwise, the project will not be realized (see Chapter 3 and Chapter 4).

Finally, if market revenues alone cannot make projects viable, support and hedging instruments are necessary to enable RE expansion. Financial support allocated in reverse auctions can be distinguished into capex support and opex support. Capex support contributes to the upfront investment costs of a project, while opex support is linked to the amount of energy fed into the grid and typically takes the form of a subsidy per unit of energy (in kilowatt-hour (kWh) or MWh) (e.g., Gephart et al., 2017). Prominent opex instruments include feed-in tariff (FIT), one- and two-sided floating feed-in premium (FIP) – the latter also known as contract for difference (CfD) – as well as guaranteed minimum prices (e.g., Anatolitis et al., 2022). A detailed discussion of these instruments is provided in Section 3.2.

1.5 Literature on RE auctions

The growing reliance on auctions stems from the development of auction theory and its practical application. McAfee and McMillan (1987a) are among the first to discuss the practical relevance of theoretical results for auctions, for example in procurement and spectrum allocation. On this basis, Haufe and Ehrhart (2018) explicitly linked auction theory to the application of auctions for RE support, offering structured and theory-based guidance for auction design and participant incentives. A rapidly growing body of research now analyzes RE auctions from multiple aspects. Several literature reviews have synthesized insights from this field (del Río and Kiefer, 2023; Fleck and Anatolitis, 2023; Anatolitis et al., 2025). Both theoretical and empirical studies are expanding in parallel. Theoretical analyses of RE auctions include Kreiss et al. (2017a), Haufe and Ehrhart (2018), Kitzing et al. (2019), Kreiss et al. (2021), Fabra (2021), and Fabra and Montero (2022), and Ehrhart et al. (2020). Another strand of literature evaluates concrete design elements and their empirical effects (del Río et al., 2015a; Gephart et al., 2017; Haelg, 2020; Szabó et al., 2020; Anatolitis et al., 2022; Anatolitis et al., 2025). For example, Anatolitis et al. (2022) assess the impact of auction design elements on awarded prices in 16 European countries, while Fleck and Anatolitis (2023) analyze the relationship between auction design elements and policy objectives.

Beyond these theory and general design analyses, an extensive literature investigates country- and sector-specific RE auctions. The AURES II project provides comprehensive comparative case analyses and national assessments across multiple countries, with a focus on Europe (e.g., Anatolitis et al., 2025; Szabó et al., 2020). Analysis beyond Europe include, for example, Tolmasquim et al. (2021) for Brazil and Rangel et al. (2024) for Colombia. The design and impact of cross-border auctions are studied in Ehrhart et al. (2019) and Bartek-Lesi et al. (2023). For different technologies, Jansen et al. (2022) provide an overview of auction designs used worldwide for offshore wind. General design issues of wind right auctions with particular reference to the US are discussed in Ausubel and Cramton (2011). Additional strands address PV auctions in Germany (Liñeiro and Müsgens, 2021), onshore wind design challenges (Liñeiro and Müsgens, 2023), multi-technology auctions (Diallo and Kitzing, 2024; Haelg, 2020), and further applications to advance clean energy in a broader sense such as heating (Blömer et al., 2022), hydrogen support (Kerres et al., 2022), and decarbonization (Winkler, 2022; Richstein et al., 2024).

Other research considers specific settings by exploring the broader effects of RE auctions on supply chains and technological innovation (del Río et al., 2020; Szabo et al., 2022), financing conditions (Amazo et al., 2021; Đukan and Kitzing, 2021; Đukan and Kitzing, 2023; Đukan et al., 2025), and market concentration (Kiefer and del Río, 2024). A different line of work, such as Woodman and Fitch-Roy (2020), uses qualitative scenario analysis to discuss the future role of auctions in European RE policy.

1.6 Approach and research questions

This thesis examines auction designs for RE expansion. The addressed topics are motivated by practical questions and problems faced by policy makers when conducting RE auctions. Across the three core chapters, the focus is on uncertainty – faced by bidders, the auctioneer, or both – and on comparing auction designs that incorporate elements to mitigate bidders' uncertainty or to address the auctioneer's uncertainty.

The approach is as follows. First, the situation is abstracted into a mathematical model. Second, the model is analyzed auction-theoretically to derive game-theoretic equilibria. Next, different mechanisms are compared theoretically with respect to the auctioneer's objectives. In addition, model extensions and variations provide further insights. Finally, conclusions and policy implications are drawn for the specific research questions.

Chapters 2 through 4 are based on three papers published or presented at international conferences. The papers have been adapted for better readability and consistency. Table 1.2 gives an overview of the papers, including authors and main methods used.

In Chapter 2, the focus is on bidders' uncertainty about future costs and on physical prequalification, modeled as costly investments in information acquisition prior to a single-

Table 1.2: Overview of the papers prepared for this thesis

Ch.	Authors	Title	Methods	Reference
2	Runxi Wang, Karl-Martin Ehrhart, Marion Ott	Mandatory vs. Voluntary a priori Investment in Information Acquisition in Procurement Auctions	Auction theory, mechanism design	Wang et al. (2025)
3	Runxi Wang, Karl-Martin Ehrhart	Designing Renewable Energy Auctions for a High Realization Probability – CfD and Payment-only Auctions	Auction theory, mechanism design	Wang and Ehrhart (2025)
4	Karl-Martin Ehrhart, Marion Ott, Stefan Seifert, Runxi Wang	Combinatorial Auctions for Renewable Energy – Potentials and Challenges	Auction theory	Ehrhart et al. (2024a)

item second-price procurement auction. As a design choice, the auctioneer can either require investment in information acquisition before the auction (mandatory setting) or allow postponed investment by the auction winner after the auction (the voluntary setting). This study complements the existing literature by analyzing the voluntary setting and comparing it with the mandatory setting. We identify different types of equilibria under different reserve prices and evaluate outcomes with respect to participation, efficiency, and expected profits. We conclude that the voluntary setting is generally favored in the analytical comparison, particularly when information costs are high.

Chapter 3 is an extended version of Wang and Ehrhart (2025) that analyzes a single-item second-price auction in which bidders have different private costs and face common uncertainty regarding future costs and revenues. The auctioneer's primary objective is to achieve a high realization probability; penalties apply in case of non-realization. Facing uncertainty about bidders' costs and risk preferences, the auctioneer must choose between two types of auction: an auction that allocates a hedging instrument CfD that eliminates revenue uncertainty, or a payment-only auction, in which the auction winner makes a payment to the auctioneer and participates in the unregulated electricity market. To the best of our knowledge, this is the first analytical study that theoretically compares CfD auctions and payment-only auctions. We show that when projects are viable without government support, the non-realization risk is higher in CfD auctions than in payment-only auctions under risk neutrality, and risk aversion further amplifies this result. When developers cannot realize projects solely with expected revenues from the electricity market, CfDs are particularly useful. Considering asymmetric information, we propose a mechanism in which developers decide competitively between a

CfD auction and a payment-only auction for a higher realization probability.

Chapter 4 systematically studies one specific auction format – combinatorial auctions (CAs) – highlighting their potentials and challenges in the context of RE auctions. This chapter focuses on a setting where the auctioneer is uncertain about bidders' valuation structures, and where complementary and substitute relationships between RE projects are prevalent. In the analysis, we consider design choices including bidding variable, bidding structure, pricing rule, reserve price, and penalty, and assess how these choices affect efficiency, bidding incentives, and non-realization risk.

Chapter 5 summarizes the findings and discusses avenues for future research.

Chapter 2

Mandatory vs. Voluntary a priori Investment in Information Acquisition in Procurement Auctions

2.1 Introduction

Procurement auctions play an essential role in securing goods or services at competitive prices. However, one of the key challenges is the uncertainty bidders face regarding future costs of fulfilling the contract they have won (see Section 1.3). This uncertainty is prominent in auctions for RE, where the auctions distribute support to RE projects (Kreiss et al., 2017b). To mitigate the uncertainty, measures such as site and environmental investigations, project specifications, and the acquisition of permits may be undertaken. The auction winners must carry out these costly measures prior to project implementation. The central question is whether these measures are executed before or after the auction. Further examples can be found in industrial and public procurement (see the second last paragraph of Section 2.1).

It is a common practice that many auctions mandate these measures as prequalification, requiring potential bidders to invest in information acquisition prior to the auctions as an essential part of project preparation (Matthäus, 2020). Such a setting is denoted as the mandatory setting. While the mandatory setting reduces uncertainty, it imposes sunk costs on participants and may exclude interested bidders, because potential bidders will only participate if the expected auction payoff exceeds the mandatory investment costs. This leads to reduced participation, a lower level of competition, and an inefficient outcome (Samuelson, 1985). In contrast, the alternative voluntary setting allows participants to decide whether to invest prior to the auction or to participate without prior investment. Participants who decide not to invest prior to the auction have to accept uncertainty and invest after winning the auction. In such a case, no additional information is released prior to the auction. Consequently, participants face a trade-off between eliminating uncertainty at sunk costs and accepting uncertainty without sunk costs.

In this chapter, we develop a theoretical model and identify the symmetric equilibria in both mandatory and voluntary settings. Our analysis complements the existing literature on the voluntary setting and on the comparison between the two settings. In the comparison, we consider reserve prices in general, efficient reserve prices, and (for the auctioneer) optimal reserve prices. The different equilibria derived from both settings are compared in terms of participation, a priori investment levels, profits of participants and the auctioneer, and efficiency. Our main results reveal several advantages of the voluntary setting, particularly its positive effects on efficiency, participation, and bidders' expected profits. A remarkable feature of the voluntary setting – absent in the mandatory setting – is the existence of mixed equilibria. In the mixed equilibria, participants choose with a certain probability either to invest in uncertainty-reducing measures before the auction or to postpone investment until after the auction if they win. Notably, the advantages of the voluntary setting rely on the coexistence of participants who invest prior to the auction and those who postpone their investment.

Both the mandatory and the voluntary settings serve as theoretical benchmarks designed to illustrate key concepts and to clarify the fundamental differences between them. Neither setting fully reflects reality. In practice, even after investment in information acquisition, uncertainty regarding future costs cannot be entirely eliminated; similarly, it is unrealistic for the auctioneer to require no project preparation at all - some degree of preparation, such as obtaining permits or defining project specifications, is necessary in nearly all auctions. Nevertheless, by abstracting from real-world complexities and focusing on the simplified theoretical benchmarks, the model allows an analytical comparison between these two settings and helps better understand the challenges in auction design.

Despite simplification, features of both mandatory and voluntary settings are typical in procurement auctions, particularly in auctions used to allocate support for RE projects (Kreiss et al., 2017b). In Germany, for example, firms planning to participate in an auction for RE support with their PV projects can decide the degree of preparation they want to perform before the auction (Bundestag, 2017). While the winning firms have to carry out investments related to site and environmental investigations, project specifications, and permitting before project implementation, these investments are not mandatory prequalifications prior to the auction. This reflects the voluntary setting. A similar framework applies to auctions for offshore wind projects (WindSeeG, 2023). On the contrary, an example for the mandatory setting can be found in auctions for onshore wind projects, that require higher a priori investment than in the cases above due to physical prequalification (Bundestag, 2017). The feature of the mandatory setting can also be observed in the context of industrial procurement auctions. For example, in the case of a large order for a newly developed product, such as an electronic or mechanical component for a new car series, suppliers build prototypes prior to production (e.g., Elverum and Welo, 2016). These prototypes represent investments in information acquisition. A purchasing company may request prototypes from all potential suppliers as a prequalification, allowing for testing and evaluation prior to the auction. In public procurement, prequalifications, such as feasibility studies or certifications that must be completed before the contract execution, are often required prior to the auction (e.g., Qiao and Cummings, 2003).

The remainder of this chapter is structured as follows. Section 2.2 reviews the relevant literature. Section 2.3 introduces the theoretical model, followed by an analysis of its equilibria in Section 2.4. Section 2.5 compares the mandatory and voluntary settings. Model extensions and discussion are provided in Section 2.6. Finally, Section 2.7 concludes.

2.2 Literature

The existing literature can be broadly divided into two interrelated strands. The first strand examines auctions with participation costs, while the second investigates auctions with information acquisition before or during the auction. Both strands focus on how potential bidders decide whether to enter an auction and how they choose to gather information – and ultimately how these decisions affect bidding strategies, auction outcomes, and overall efficiency.

In the early work on auctions with participation costs, Samuelson (1985) and McAfee and McMillan (1987b) formalize the role of participation costs, showing that costly entry can reduce competition and that the optimal reserve price equals the auctioneer's valuation. Their analyses confine themselves to pure strategy equilibria, where only bidders with valuations above a certain threshold (cutoff type) participate. Similar settings are investigated in Tan and Yilankaya (2006) and Celik and Yilankaya (2009), who also study asymmetric equilibria. In contrast, Levin and Smith (1994) introduce mixed entry strategies, where potential bidders enter the auction with a certain probability — the so-called randomized participation. They also extend the well-known revenue-equivalence theorem, which is confirmed by Menezes and Monteiro (2000). Jehiel and Lamy (2015) also allow randomized participation and studies discrimination in auction participation between incumbents and new entrants. Our model is similar to theirs for new entrants. More recently, Gillen et al. (2017) introduce empirical perspectives on participation costs.

Complementing this literature, a second strand focuses on the cost of information acquisition. Unlike participation costs, which serve solely as entry barriers, information acquisition costs help potential bidders learn their true valuations and thus influence their decision-making. Stegeman (1996) extends the classical participation cost models by jointly considering participation costs and information acquisition in a single-unit independent private values setting, showing that the second-price auction induces efficient information acquisition. Bergemann and Välimäki (2002) studies information acquisition prior to mechanism selection, proving that the Vickrey-Clarke-Groves (VCG) mechanism provides optimal incentives for ex-ante learning and ex-post efficiency in every private value setting. Following their definition of efficiency given certain information, our model yields similar results. The main difference with our model is that bidders only invest in information acquisition before the auction by deciding how much to invest. In our model, information acquisition is part of the total investment that must be made by the auction winner in any case. The question is when – before or after the auction.

Further, Schweizer and Szech (2017) introduces dispersion criteria to classify circumstances under which revenue incentives dominate welfare incentives in information release. More recent papers compare different auction formats: Compte and Jehiel (2007) considers a model where bidders are either fully informed or completely uninformed and shows that ascending auctions encourage more information acquisition and yield higher revenue for the auctioneer than static formats. Similarly, when information acquisition costs are low, Gretschko and Wambach (2014) shows that dynamic auction formats outperform static auction formats in terms of efficiency. The most recent paper, Gretschko and Simon (2024), analyzes a setting where participants can covertly acquire information over time. They show that the dynamic pivot mechanism provides the right incentives to follow the information acquisition recommendations and to report truthfully, and therefore can implement any first-best information acquisition and allocation rule.

Together, these papers provide a comprehensive foundation for analyzing how participation costs and information acquisition influence auction design, strategic behavior, and efficiency. Based on these insights, our work complements the existing literature on the voluntary setting and on the comparison between mandatory and voluntary settings.

2.3 Model

We consider a single-unit procurement auction with N potential bidders (firms), where N is finite and $N > 2$. The lowest bid wins and the second lowest bid determines the price (Vickrey, 1961). The choice of a second-price auction is well established in the related literature (see e.g., Ganuza and Penalva, 2010; Schweizer and Szech, 2017). The auctioneer has a maximum willingness to pay of x_0, $x_0 > \underline{x}$ and sets a reserve price r, $\underline{x} < r \leq x_0$. If the auction results in a winning bidder, x_0 also represents the value of the fulfilled procurement to the auctioneer.

All firms are risk-neutral expected-utility maximizers and a priori symmetric. Each firm

i has private cost x_i, which is a priori unknown to the firm, and x_i is the realization of the random variable $X_i, i \in \{1, ..., N\}$. The X_i are independent and identically distributed with the distribution function F and the density function f on the support $[\underline{x}, \bar{x}]$. The realization of X_i is known only after an investment c in information acquisition. The investment cost c is the same for all firms, which is sensible as all firms with similar products or projects face similar preparations.[1] All assumptions above are common knowledge. Since c will be incurred for the auction winner in any case, the firm's individual cost of producing the product or implementing the project is $x_i + c$. A similar approach can be found in Jehiel and Lamy (2015), which corresponds to our mandatory setting, while our model extends their model to include the voluntary setting and full participation.

In the mandatory setting, the auctioneer requires participants to invest in information acquisition before participating in the auction. That is, all participants are investors who have already learned their true costs x_i when submitting their bids and c is sunk cost. Therefore, all participants will bid truthfully in the second-price auction if $x_i \leq r$ or will not bid if $x_i > r$.

In the voluntary setting, it is up to the participants whether or not they invest in information acquisition prior to the auction. However, the auction winner must undertake this investment at the latest after the auction. If a participant chooses to invest c to learn its own cost, it is referred to as an investor. Alternatively, if a participant decides not to invest, no additional information is revealed other than the common knowledge, and it is referred to as a non-investor. In the auction, an investor will bid truthfully if $x_i \leq r$ or will not bid if $x_i > r$, as in the mandatory setting, while a non-investor will bid $\mathbb{E}[X_i] + c$ as the dominant strategy in terms of expected profit if $\mathbb{E}[X_i] + c \leq r$, or will not bid if $\mathbb{E}[X_i] + c > r$ (Ehrhart et al., 2015). Since the firms are a priori symmetric, we omit the index i and set $\mathbb{E}[X_i] =: \mathbb{E}[X]$ for simplicity.

2.4 Equilibria and properties

This section presents symmetric equilibria of the model and their properties. The key findings for both settings are summarized in two propositions, which characterize the strategic behavior and the expected outcomes of the firms. These propositions are further supported by several lemmas that analyze equilibrium properties and aid in their proofs. For completeness, derivations and proofs can be found in Appendix A.

The equilibria differ in the probability of participation and the probability of being an

[1] It is mostly unrealistic to invest partially in information acquisition by conducting only a lower level of project preparation, as it is unreasonable to prepare only half a prototype, or half a permit. See Section 2.6.2 for model discussion. Moreover, c can also be interpreted as the expected value of the symmetric random variable C, allowing different realization of the investment cost. Nevertheless, this extension does not change the results of our model below, because for the investment decisions, only the expected investment cost c is relevant; after the investment is made, the realized C is sunk cost and thus is not considered in future decisions.

investor or a non-investor. If firms in the mandatory setting or in the voluntary setting participate only as investors, their participation probability is denoted by q. If firms in the voluntary setting participate with a strategy with mixed investment behavior, and q_1 and q_2 denote the probabilities of investor and non-investor behavior, respectively, where $q_1 + q_2 \leq 1$ is the participation probability. If firms in the voluntary setting participate only as non-investors, their participation probability is denoted by q'.

Three relevant thresholds characterize the equilibria below and are given by

$$c_{max}(r) := \int_{\underline{x}}^{r} (r-t)f(t)ds = \int_{\underline{x}}^{r} F(t)ds,$$

$$c^m_{min}(r) := \int_{\underline{x}}^{r} F(t)(1 - F_{(1,N-1)}(t))dt,$$

$$c^v_{min}(r) := \int_{\underline{x}}^{r} F(t)(1 - F_{(1,N-1)}(t))dt - \int_{\mathbb{E}[X]+c}^{r} (1 - F_{(1,N-1)}(t))dt, \text{ for } r \geq \mathbb{E}[X] + c.$$

Depending on r, $c_{max}(r)$ denotes the highest value of c for which an equilibrium with participation exists, while $c^m_{min}(r)$ and $c^v_{min}(r)$ denote the lowest values of c such that a slight increase in c would prevent full participation and investment in the mandatory and voluntary setting, respectively.

Lemma 1. *For any distribution, it holds that* $0 < c^m_{min}(r) < c_{max}(r)$*, and additionally* $0 < c^v_{min}(r) \leq c^m_{min}(r)$*, if* $c^v_{min}(r)$ *exits.*

Given Lemma 1, we have the following propositions.

Proposition 1. *In the mandatory setting, the following applies:*

(i) For all $c \in [0, c^m_{min}(r)]$*, there exists a unique equilibrium, where* $q = 1$ *(i.e. full participation). The expected profit of each participant is weakly positive.*

(ii) For all $c \in (c^m_{min}(r), c_{max}(r))$*, there exists a unique equilibrium, which is characterized by a unique* $q \in (0,1)$ *(i.e. randomized participation), determined by*

$$\pi^m = \sum_{n=0}^{N-1} P(n,q) \int_{\underline{x}}^{r} F(t)(1-F(t))^n dt = c. \tag{2.1}$$

The expected profit of each participant is zero.

(iii) For all $c \geq c_{max}(r)$*, there exists a unique equilibrium, where* $q = 0$ *(i.e. no participation).*

In the mandatory setting, if the investment cost c is very low (depending on r) or even zero, it is worthwhile for all firms to participate and invest, leading to a positive expected profit.[2] As c increases towards the threshold $c^m_{min}(r)$, the expected profit decreases. At the threshold, firms are indifferent between participating or not, as their expected profit is zero. If c increases further, full participation would result in negative profits, making it infeasible. However, an equilibrium exists in the form of randomized participation, where all firms participate with probability $q \in (0,1)$, so that their expected profit is zero and thus all firms remain indifferent between participating or not. As c approaches the upper threshold $c_{max}(r)$, the participation probability q decreases to zero. Beyond this point, participation is no longer worthwhile.

For the cases of our main focus, where $c \in (c^m_{min}(r), c_{max}(r))$, and equilibria with randomized participation exist, we have the following lemmas (proofs can be found in Appendix A.1).

Lemma 2. *It holds that* $\frac{\partial \pi^m}{\partial r} > 0$, $\frac{\partial \pi^m}{\partial q} < 0$, *and* $\frac{\partial \pi^m}{\partial N} < 0$.

Lemma 2 states that the expected payoff increases in r and decreases in q and N. Therefore, to satisfy the equilibrium condition (2.1), we have the following: $\frac{dq}{dr} > 0$, $\frac{dq}{dc} < 0$, $\frac{dq}{dN} < 0$. That is, a higher reserve price, lower information costs, and less competition increase participation.

Lemma 3. *Given N, c, and r, for a distribution F_K that is mean-preserving contraction of F with support $[\underline{\kappa}, \overline{\kappa}]$ and $\frac{\mathbb{E}[K]-\underline{\kappa}}{\mathbb{E}[X]-\underline{x}} = \frac{\overline{\kappa}-\mathbb{E}[K]}{\bar{x}-\mathbb{E}[X]}$, the probability of participation corresponding to q is less than q.*

Since F_K is a mean-preserving contraction of F, whose distribution is proportionally contracted to a narrower support, for the random variable K with distribution F_K, $\mathbb{E}[K] = \mathbb{E}[X]$ applies. Lemma 3 implies that, the wider the distribution, the higher q will be. This is because, given the same conditions, including the same information costs, the information gain from wider distribution is higher, which favors investment.

Proposition 2. *In the voluntary setting, the following applies:*

(i) If $r < \mathbb{E}[X] + c$, the equilibria and their conditions are the same as in the mandatory setting.

(ii) If $r = \mathbb{E}[X] + c$, it holds that:

For all $0 \leq c \leq c^v_{min}(r) = c^m_{min}(r)$, there exists a unique equilibrium, where $q = 1$ (i.e. full participation and investment). The expected profit of each participant is weakly positive.

[2] In this section, as we focus on the strategic behavior of the firms give c and r, expected profit refers specifically to the expected profit of the participants. In the following sections, where the auctioneer's profit is also considered, we will clearly distinguish between the expected profit of the participants and that of the auctioneer.

For all $c \in (c^m_{min}(r), \bar{x} - \mathbb{E}[X])$, there exists two types of equilibria: The first type is an equilibrium, where $q \in (0,1)$ (i.e. randomized participation and investment), determined by

$$\sum_{n=0}^{N-1} P(n,q) \int_{\underline{x}}^{r} F(t)(1-F(t))^n dt - c = 0. \tag{2.2}$$

The expected profit of each participant is zero. The second type are equilibria, where $q_1 = q \in (0,1)$ as determined by Equation (2.2) and $q_2 \in (0, 1-q_1]$ arbitrarily (i.e. randomized participation and mixed investment behavior). The expected profit of each participant is zero.

For all $c \geq \bar{x} - \mathbb{E}[X]$, there exists equilibria, where $q' \in (0,1]$ arbitrarily (i.e. randomized participation without investment). The expected profit of each participant is zero.

(iii) If $r > \mathbb{E}[X] + c$, it holds that:

For all $0 \leq c \leq c^v_{min}(r)$, there exists a unique equilibrium, where $q = 1$. The expected profit of each participant is strictly positive.

For all $c \in (c^v_{min}(r), \bar{x} - \mathbb{E}[X])$, there exists a unique equilibrium, where $q_1 \in (0,1)$ and $q_2 = 1 - q_1$ (i.e. full participation and mixed investment behavior), and q_1 is determined by

$$\sum_{n_1=0}^{N-1} P(n_1,q_1) \int_{\underline{x}}^{\mathbb{E}[X]+c} F(t)(1-F(t))^{n_1} dt - P(N-1,q_1) \int_{\mathbb{E}[X]+c}^{r} (1-F(t))^N dt - c = 0. \tag{2.3}$$

The expected profit of each participant is strictly positive.

For all $c \geq \bar{x} - \mathbb{E}[X]$, there exists a unique equilibrium, where $q' = 1$ (i.e. full participation without investment). The expected profit of each bidder is zero.

In the voluntary setting, the equilibria depend on the relationship between $\mathbb{E}[X] + c$ and r. Since the bid of a non-investor is $\mathbb{E}[X] + c$, firms may participate as non-investors in the auction only if $r \geq \mathbb{E}[X] + c$. If $r < \mathbb{E}[X] + c$, firms do not participate as non-investors and thus the equilibria and their conditions are the same as in the mandatory setting.

In case $r = \mathbb{E}[X] + c$, the participation of non-investors is arbitrary and in addition to the participation of investors in the mandatory setting, as long as the mandatory setting does not yield full participation. That is, for each $c > c^m_{min}(r)$, where $q \in [0,1)$ in the mandatory setting, there exist equilibria in mixed investment behavior with $q_1 = q$ and any $q_2 \in [0, 1-q]$ in the voluntary setting. The reason is that q_2 has no additional effect on the expected profit of both the investors and the auctioneer than the reserve price r and the non-investors' expected profit is zero. This is a special case exactly because of the equality $r = \mathbb{E}[X] + c$.

In case $r > \mathbb{E}[X] + c$, the non-investors will always expect a positive profit, unless all potential bidders participate as non-investors. Therefore, all firms have an incentive to participate, either as an investor with probability q_1 or as a non-investor with probability $q_2 = 1 - q_1$. If c is very low or even zero, it is worthwhile for all firms to participate and invest $(q = 1)$. As c increases, the expected profit decreases. In contrast to the mandatory setting, the expected profit of the non-investors catches the expected profit of the investors before it falls to zero. That is, at a lower threshold of c than in the mandatory case $(c^v_{min} \leq c^m_{min})$, not all participants will invest. From here on, the equilibrium strategy changes to a mixed investment behavior with $q_2 = 1 - q_1 > 0$. Note that in this equilibrium, the coexistence of investors and non-investors is necessary: Both types rely on the existence of each other to sustain the equilibrium. As c further increases, the advantage of non-investors over investors increases because the value of the information gain remains unchanged but the information cost increases. As a result, as c increases from the threshold c^v_{min} to the threshold $\bar{x} - \mathbb{E}[X]$, q_1 decreases from 1 to 0, while q_2 increases from 0 to 1. Beyond the threshold $\bar{x} - \mathbb{E}[X]$, there are only non-investors $(q' = 1)$ and thus the the expected profit is zero. If $q' < 1$, the expected profit would be strictly positive, so that all firms have an incentive to participate, which raises the participation probability to 1 and lowers the expected profit to zero. The equilibria at low c with $q = 1$ and high c with $q' = 1$ can be seen as a continuous extension of the equilibria in mixed investment behaviour at the two extremes $q_1 = 1$ and $q_2 = 1$.

For the cases of our main focus with $r > \mathbb{E}[X] + c$ and $c \in (c^v_{min}(r), \bar{x} - \mathbb{E}[X])$ so that the equilibrium in mixed investment behaviour exists (with $q_1 + q_2 = 1$), we have the following lemmas (proofs can be found in Appendix A.2).

Lemma 4. *Let* $\Delta\pi^v = \pi^{vi} - c - \pi^{vn}$, *it holds that* $\frac{\partial \Delta\pi^v}{\partial r} < 0$, $\frac{\partial \Delta\pi^v}{\partial c} < 0$, $\frac{\partial \Delta\pi^v}{\partial q_1} < 0$, *and* $\frac{\partial \Delta\pi^v}{\partial N} < 0$.

The term $\Delta\pi^v$ is the difference in expected profits between investors $(\pi^{vi} - c)$ and non-investors (π^{vn}) in the voluntary setting. Lemma 4 states that $\Delta\pi^v$ decreases in r, c, q_1, and N. To satisfy the equilibrium condition (2.3), given any two of three variables r, c, and N, the probability of investment q_1 decreases in the third variable: $\frac{dq_1}{dr} < 0, \frac{dq_1}{dc} < 0, \frac{dq_1}{dN} < 0$. Both investors and non-investors benefit from a higher r, but non-investors benefit more. Similarly, while increased competition harms both groups, investors are more adversely affected. Additionally, investors incur the cost c, whereas non-investors do not. As a result, a higher r, c or N increases the relative advantage of non-investors over investors, leading to a lower q_1. Overall, an increase in r, c, or N speaks in favor of non-investment and thus shifts the equilibrium in mixed investment behavior towards more non-investors.

Lemma 5. *Given* N, c, *and* r, *for a distribution* F_K *that is mean-preserving contraction of* F *with support* $[\underline{\kappa}, \overline{\kappa}]$ *and* $\frac{\mathbb{E}[K] - \underline{\kappa}}{\mathbb{E}[X] - \underline{x}} = \frac{\overline{\kappa} - \mathbb{E}[K]}{\bar{x} - \mathbb{E}[X]}$, *the probability of participation corresponding to* q_1 *is less than* q_1.

Analogous to Lemma 3, Lemma 5 implies that a wider distribution of information favors investment and thus leads to a higher q_1.

In total, our analysis identifies five types of symmetric equilibria depending on c and r, which are classified and labeled below:

- E_0: No participation, $q = 0$
- E_1^f: Full participation, all firms participate and invest c, $q = 1$
- E_1^r: Randomized participation, all firms participate and invest c with probability $q \in (0, 1)$
- E_2: All firms participate without investment with probability $q' \in (0, 1]$
- E_{mix}: Mixed investment behavior, all firms participate and invest c with probability $q_1 \in (0, 1)$ and participate without investment with $q_2 \in (0, 1)$ where $q_1 + q_2 \leq 1$

These equilibria are summarized and illustrated in Figure 2.1, Table 2.1, and Table 2.2.

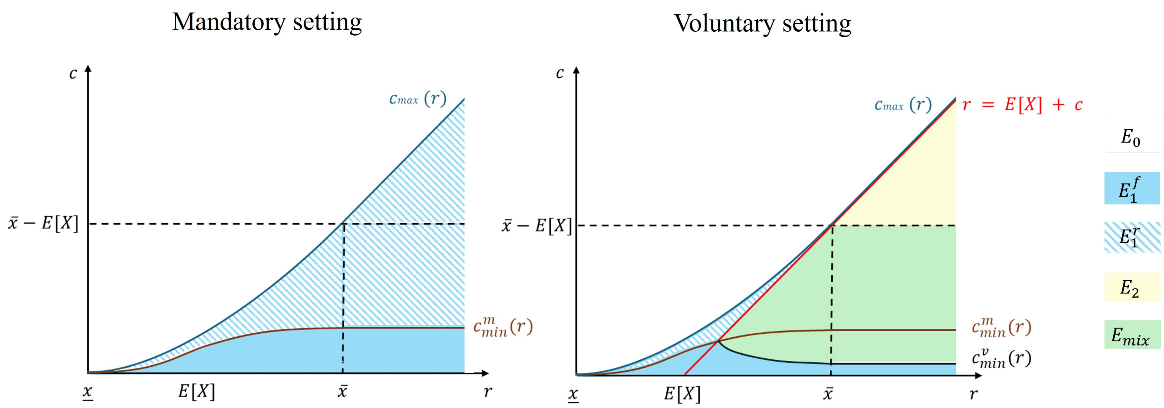

Figure 2.1: Equilibria depending on c and r in mandatory and voluntary settings

Table 2.1: Equilibria in the mandatory setting

Condition	Equilibrium	Characteristics
$0 \leq c \leq c^m_{min}(r)$	E_1^f	$q = 1, \pi^m \geq 0$
$c^m_{min}(r) < c < c_{max}(r)$	E_1^r	$q \in (0, 1), \pi^m = 0$
$c \geq c_{max}(r)$	E_0	No participation

Table 2.2: Equilibria in the voluntary setting

	Condition	Equilibrium	Characteristics
$r < \mathbb{E}[X] + c$	$0 \leq c \leq c^m_{min}(r)$	E^f_1	$q = 1, \pi^{vi} \geq 0$
	$c^m_{min}(r) < c < c_{max}(r)$	E^r_1	$q \in (0,1), \pi^{vi} = 0$
	$c \geq c_{max}(r)$	E_0	No participation
$r = \mathbb{E}[X] + c$	$0 \leq c \leq c^m_{min}(r) = c^v_{min}(r)$	E^f_1	$q = 1, \pi^{vi} \geq 0$
	$c^m_{min}(r) < c < \bar{x} - \mathbb{E}[X]$	E^r_1 & E_{mix}	$q_1 \in (0,1), q_2 \in [0, 1 - q_1]$, $\pi^{vi} = \pi^{vn} = 0$
	$c \geq \bar{x} - \mathbb{E}[X]$	E_2	$\pi^{vn} = 0$
$r > \mathbb{E}[X] + c$	$0 \leq c \leq c^v_{min}(r)$	E^f_1	$q = 1, \pi^{vi} > 0$
	$c^v_{min}(r) < c < \bar{x} - \mathbb{E}[X]$	E_{mix}	$q_1, q_2 \in (0,1),\ q_1 + q_2 = 1$, $\pi^{vi} = \pi^{vn} > 0$
	$c \geq \bar{x} - \mathbb{E}[X]$	E_2	$q_2 = 1, \pi^{vn} = 0$

2.5 Comparison between mandatory and voluntary settings

In this section, we compare the mandatory and voluntary settings under three reserve price schemes: reserve prices in general (identical for both settings), the efficient reserve price and the (for the auctioneer) optimal reserve prices. The comparison focuses on participation, a priori investment levels, profits of participants and auctioneer, and efficiency (expected welfare). To avoid redundancy, we restrict attention to cases in which the two settings yield different equilibria, i.e., when $r \geq \mathbb{E}[X] + c$ and $c > c^v_{min}(r)$. Since all comparisons involve weak orderings, the results below naturally also apply to cases where the two settings yield the same equilibrium.

2.5.1 Comparison under reserve price in general

First, consider the scheme in which both settings share the same but unspecified reserve price. Then, the following results hold. The formal analysis is provided in Appendix A.3.

Proposition 3. *For any pair of c and r, the voluntary setting yields a weakly higher total participation probability but a weakly lower probability of a priori investment compared to the mandatory setting.*

That is, although the expected number of investors in the voluntary setting is weakly lower than in the mandatory setting, the total expected number of participants is higher in the voluntary setting due to the presence of non-investors.

Proposition 4. *For any pair of c and r, participants always expect weakly higher profits in the voluntary setting than in the mandatory setting.*

That is, given the same auction environment, all firms will weakly prefer the voluntary setting over the mandatory one. Although the voluntary setting offers participants an additional degree of freedom in their decision, it is uncertain that they will benefit from it. Thus, this result is nontrivial. Since the model is game-theoretic rather than decision-theoretic, having more strategic options does not necessarily imply better outcomes. For example, the introduction of an additional strategy to the players' strategy set in a game, which induces a new equilibrium similar to a prisoner's dilemma, leads to strictly lower profits for the players despite their increased degree of freedom.

In the following subsections, we introduce the auctioneer as a designer who can use the reserve price to serve its own objective: either by setting the efficient reserve price to maximize expected welfare, or by setting the optimal reserve price to maximize its own expected profit. Note that the reserve price may differ between the mandatory and voluntary settings.

2.5.2 Comparison under efficient reserve price

A second-price auction with $r = x_0$ implements the (interim) efficient mechanism in both settings. This follows from the characteristics of the sunk costs c. Since these costs are incurred prior to the auction, they are not welfare-relevant at the time of the auction. Even immediately after the auction – in the voluntary setting before the winning bidder invests, if this has not already occurred – the result is still efficient given the available information. A similar statement can be found in Bergemann and Välimäki (2002).

Given c and x_0, since the efficient reserve price is the same in both setting, Proposition 3 and 4 apply under the efficient reserve price. That is, the voluntary setting yields weakly higher expected participation, weakly lower expected investment level, and weakly higher expected profits of the participants than the mandatory setting.

To compare the two settings from the auctioneer's perspective, we use expected welfare as the measure of efficiency. Welfare consists of two parts: The value the auctioneer receives from either fulfilled or unfulfilled procurement, and the associated total costs. If the auction results in a winning bidder, the value of the fulfilled procurement to the auctioneer is x_0, and the costs incurred include $x_{winner} + c$ and the investment costs of the remaining participants. If there is no participation, the value of the unfulfilled procurement to the auctioneer is 0, and no costs are incurred. If there are participants but no bids are submitted (due to higher realized private costs than the reserve price), the value of the unfulfilled procurement to the auctioneer is 0, while all participants bear their investment costs.

Proposition 5. *Given $r = x_0$, the voluntary setting always equals or exceeds the mandatory setting in terms of expected welfare.*

On the boundary $x_0 = r = \mathbb{E}[X] + c$, the expected welfare is the same in the mandatory and voluntary settings, as the participation of the non-investors does not raise the welfare gain. Within E_{mix} and E_2, the difference in expected welfare between voluntary and mandatory settings increases in c if $c \in (c^v_{min}(x_0), c^m_{min}(x_0))$, decreases in c if $c > c^m_{min}(x_0)$ and weakly increases in x_0. That is, the voluntary setting has its maximum advantage in expected welfare over the mandatory setting if $x_0 \geq \bar{x}$ and $c = c^m_{min}(x_0)$. See Appendix A.4 for the proof of Proposition 5.

2.5.3 Comparison under optimal reserve price

To compare the two settings under their respective optimal reserve prices, we first determine the optimal reserve price as a function of x_0 given c. We first consider the locally optimal reserve price for each equilibrium with participation summarized in Table 2.3, under the assumption that the equilibrium type remains unchanged at the locally optimal reserve price.

Table 2.3: Locally optimal reserve prices r^* in different equilibria

Equilibrium	Optimal reserve price r^*
E_1^f	$r^* = x_0 - \frac{F(r^*)}{f(r^*)}$
E_1^r	$r^* = x_0$
E_2	Any $r^* \in [\bar{x}, x_0]$ is optimal, in particular $r^* = x_0$ is efficient
E_{mix}	$r^* \leq x_0 - \frac{F(r^*)}{f(r^*)}$

In E_1^f, due to full participation, the classical optimal reserve price applies, i.e. $r^* = x_0 - \frac{F(r^*)}{f(r^*)}$, which is independent of N (Myerson, 1981). Define $\gamma_m(r^*) = r^* + \frac{F(r^*)}{f(r^*)} = x_0$. Assume that $\frac{F(x)}{f(x)}$ is increasing in x, which is a standard assumption satisfied by most common distributions. Then $\frac{dr^*}{dx_0} > 0$, and the shading term $\frac{F(r^*)}{f(r^*)}$ increases in x_0 and is strictly positive whenever $x_0 > \underline{x}$. In E_1^r, due to randomized participation ($q \in (0, 1)$) and zero expected payoff, Jehiel and Lamy (2015) show that the efficient reserve price is also optimal, i.e., $r^* = x_0$. In the special case $x_0 = \mathbb{E}[X] + c$, we have $r^* = x_0$, since the additional participation of the non-investors has no effect on the auctioneer's expected profit. If $x_0 > \mathbb{E}[X] + c$: In E_2, since $q' = 1$, the price is not determined by the reserve price, so any reserve price between $\bar{x}$ and x_0 is optimal. In particular, the efficient reserve price $r^* = x_0$ is also an optimal reserve price. In E_{mix}, where $q_1 + q_2 = 1$, full participation occurs. Nevertheless, the presence of non-investors weakens competition compared to E_1^f, leading to a lower optimal reserve price, i.e., $r^* \leq x_0 - \frac{F(r^*)}{f(r^*)}$ (see Appendix A.5). Let $\gamma_v(r^*) = x_0$, we have $\frac{dr^*}{dx_0} > 0$.

All locally optimal reserve prices are monotonically increasing in x_0 and this monotonicity should also not be violated across the equilibria; otherwise more firms will be excluded at a higher x_0, which cannot be optimal.

In the next step, we consider the globally optimal reserve price $r_m^*(x_0)$ and $r_v^*(x_0)$ given c. According to the argument above, within an equilibrium, an increase in x_0 leads to an increase in both $r_m^*(x_0)$ and $r_v^*(x_0)$. At the intersection point where the equilibrium will change to a different one (from the left equilibrium to the right equilibrium in Figure 2.1), the globally optimal reserve price should be the maximum of the locally optimal reserve price at the intersection point (in the left equilibrium) and the locally optimal reserve price on the right side of it (in the right equilibrium) due to the monotonicity. Note that $x_0 > (\gamma_m)^{-1}(x_0) \geq (\gamma_v)^{-1}(x_0)$, so for each c, the direct equilibrium change from a lower x_0 (left) to a higher x_0 (right) always leads to a lower locally optimal reserve price. That is, the globally optimal reserve price should first remain unchanged in the locally one at the intersection point in the left equilibrium, until being caught but the locally optimal reserve price in the right equilibrium. For example, in the voluntary setting with $c_{min}^m(\bar{x}) \leq c < \bar{x} - \mathbb{E}[X]$, at the intersection point $x_0 = \mathbb{E}[X] + c$ we have $r_v^*(x_0) = \mathbb{E}[X] + c$ and for $\mathbb{E}[X] + c < x_0 \leq \gamma_v(\bar{x})$ we have $r_v^*(x_0) = \max\{\mathbb{E}[X] + c, (\gamma_v)^{-1}(x_0)\}$, that is

$$r_v^*(x_0) = \begin{cases} \mathbb{E}[X] + c, \text{ if } \mathbb{E}[X] + c < x_0 \leq \gamma_v(\mathbb{E}[X] + c) \\ (\gamma_v)^{-1}(x_0), \text{ if } \gamma_v(\mathbb{E}[X] + c) < x_0 \leq \gamma_v(\bar{x}) \end{cases}$$

as illustrated in Figure 2.2.[3]

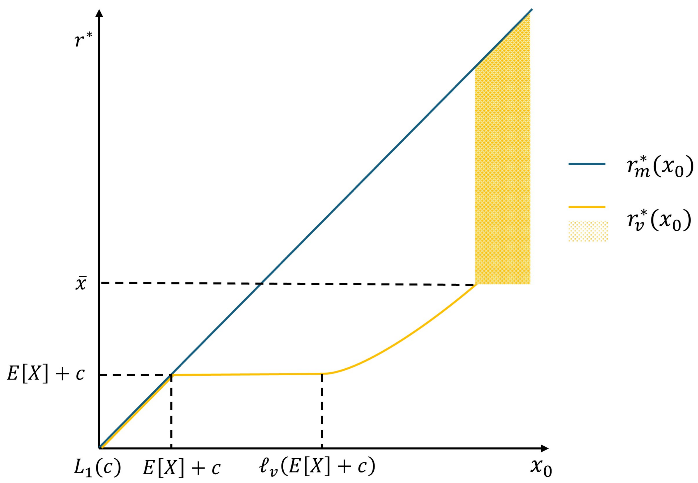

Figure 2.2: Exemplary optimal reserve price

Under the different optimal reserve prices derived above, Proposition 3 still holds, provided that $q_2 = 1 - q_1$ in case $r = \mathbb{E}[X] + c$.

[3] Note that $\gamma_v(\mathbb{E}[X] + c)$ can be very large. For example, under uniform distribution, $\gamma_v(\mathbb{E}[X] + c) > 2\mathbb{E}[X] + 2c > \bar{x}$.

However, Proposition 4 no longer applies in general. Given $x_0 > \mathbb{E}[X] + c$, the different optimal reserve prices in two settings can lead to different equilibria, making participants' expected profits not directly comparable. Beside the effect that participants do not necessarily benefit from the increased degree of freedom, the auctioneer can also exploit the increased flexibility by setting different reserve prices. Thus, without further analysis, no general conclusion can be drawn on participants' expected profits.

Proposition 6. *Given $r_m^*(x_0)$ and $r_v^*(x_0)$, for $c \geq c_{min}^m(\bar{x})$, participants expect weakly higher profits in the voluntary setting than in the mandatory setting.*

Proposition 6 states that given the optimal reserve price, as long as the information cost c is so high that potential bidders are excluded in the mandatory setting, participants expect weakly higher profits in the voluntary setting. We consider this case to be relevant in practice, as the main motivation for the voluntary setting lies in the fact that the sunk information cost in the mandatory setting excludes potential bidders. In the contrast, with a lower c, where E_1^f exists in the mandatory setting and E_{mix} in the voluntary setting, the mandatory setting yields higher expected profits for the participants at some x_0 (see Appendix A.5).

Proposition 7. *Given $r_m^*(x_0)$ and $r_v^*(x_0)$, either the voluntary or the mandatory setting can yield a higher expected profit for the auctioneer, depending on c, x_0, and F.*

Finally, we compare the expected profit of the auctioneer. Given the optimal reserve price, either setting can be preferred, depending on c and x_0. In general, a high information cost c tends to favor the voluntary setting. We have shown that in the equilibrium E_2, or when c approaches $\bar{x} - \mathbb{E}[X]$ in the equilibrium E_{mix}, the auctioneer expects higher profit in the voluntary setting. Conversely, when c approaches $c_{min}^m(r)$ within the equilibrium E_{mix}, the auctioneer expects higher profit in the mandatory setting (see Appendix A.5).

2.6 Model extensions and discussion

Our model contributes to the broader discussion of auction design and procurement policy by comparing two theoretical benchmarks, but it abstracts from certain practical complexities that warrant extension and discussion.

2.6.1 Risk aversion

While the model assumes risk-neutral firms, it can be extended to incorporate risk aversion, which is often a more realistic assumption in practice (e.g., Salm, 2018; Abate et al., 2022). This extension provides a more nuanced understanding of the difference between mandatory and voluntary settings and allows for a better representation of the real world.

In a risk-averse setting, the weakly dominant bidding strategy in a second-price auction remains unchanged. Investors will truthfully bid their known private costs, and non-investors will bid their certainty equivalent of their uncertain total private costs (Ehrhart et al., 2015). Specifically, a non-investor i will bid $CE_{X_i} + c$, where CE_{X_i} is the certainty equivalent of the uncertain private cost X_i. The non-investor is exactly indifferent between winning the auction with this bid and not winning the auction. Since risk aversion implies $CE_{X_i} > \mathbb{E}[X_i]$, the non-investor demands a risk premium $CE_{X_i} - \mathbb{E}[X_i]$. Assuming symmetric and equally risk-averse firms, all firms have the same certainty equivalent CE_X, which shifts the relevant reserve price threshold for non-investors from $\mathbb{E}[X] + c$ to $CE_X + c$.

Risk aversion has a different effect on participation in the two settings. Since non-investors can price their risk into their bids while investors cannot, risk aversion reduces the participation probability of investors. This leads to a lower participation probability in the mandatory setting and a lower share of investors in the voluntary setting, because the perceived risk of incurring high costs outweighs the potential benefits of investing in information while incurring sunk costs.

Compared to the risk-neutral setting, as illustrated in Figure 2.1, risk aversion shifts the key threshold quantitatively, but leaves the structure of the equilibria unchanged. In particular, the red threshold, which marks the lower bound of the reserve price where non-investors may exist in the equilibrium, shifts parallel to the right by the risk premium. The thresholds $c_{max}(r)$, $c^m_{min}(r)$, and $c^v_{min}(r)$ move downward.

At the first glance, it may seem counterintuitive that non-investors, who face greater uncertainty while bidding, would participate relatively more than investors under risk aversion. However, the sunk cost dynamic changes the picture: Investors who have already incurred these costs face a greater risk of losing their investment if they do not win the auction. This makes them more vulnerable to the risk. In contrast, non-investors can better hedge against risk through their certainty equivalents and thus improve their position relative to investors in a risk-averse setting.

In summary, risk aversion causes non-investors to participate at higher reserve prices relative to risk neutrality, but then with a relative advantage over investors due to their ability to account for risk with their bids.

2.6.2 Partial a priori investment in information acquisition

As mentioned above, it is generally unrealistic to conduct only part of the project preparation. However, in case of multiple preparation steps or measures (such as obtaining different types of permits), it may be possible to complete a subset of project preparation, i.e., to make partial a priori investment, which can result in partial information acquisition.

The mixed investment behavior with $q_1 + q_2 = 1$ in our model can be alternatively interpreted as a pure strategy, where $q_1 \in [0,1]$ denotes the investment level instead of the investment probability. That is, all firms make a partial a prior investment of size $q_1 c$ in information acquisition, and learn their true costs with probability q_1, while no information is revealed with probability q_2.

A possible extension for future research is to explicitly model partial information revelation resulting from partial investment. In such a model, a partial investment of size $q_1 c$ could reveal an imprecise signal about a bidder's private cost. The precision of this signal is positive correlated with q_1. The residual uncertainty regarding private cost can be represented by a zero-mean noise term, whose distribution and support shrink with q_1. This extension captures the intuitive idea that a higher level of investment reduces, but does not necessarily eliminate, cost uncertainty. This corresponds to the approach of Bergemann and Välimäki (2002).

2.6.3 Limitations

A key limitation of the model is the assumption that the auction outcome is binding. In practice, however, this is often not the case – especially for non-investors in our model, who may commit to a project based on expected rather than realized costs. After winning the auction, these bidders may face unforeseen challenges such as unfavorable geological or meteorological conditions, technical complications, ecological constraints, or delays in permitting processes. These factors can significantly increase project costs or create barriers to implementation. If such ex-post costs significantly exceed initial expectations, this may lead to a decision not to proceed with the project despite the incurred sunk costs.

This phenomenon has been observed in several procurement auctions. For example, in the German onshore wind auction, less than half of the so-called citizen energy projects, which had lower prequalifications for the auction than the projects of other energy companies, were ultimately realized (Liñeiro and Müsgens, 2023), indicating the discrepancy between auction results and project realization.

In addition to prequalification requirements, other commonly discussed instruments to mitigate the non-realization risk include penalties and financial securities (Kreiss et al., 2017b). Both instruments are intended to strengthen commitment by increasing the cost of strategic default. However, because bidders incorporate potential penalties when bidding, the weakly dominant strategy of truthful bidding in second-price auctions no longer holds. Moreover, the effectiveness of penalties is limited in practice. Penalties may be unpaid if the winning firm declares bankruptcy. Besides, high financial security requirements can act as entry barriers, potentially excluding financially weaker but otherwise efficient participants.

Further discussion of the measures against the non-realization risk and their effects on equilibrium outcomes is beyond the scope of this work.

2.7 Conclusion

This chapter contributes to the existing literature by providing a comprehensive analytical comparison between mandatory and voluntary a priori investment in information acquisition in procurement auctions. We develop a theoretical model that characterizes five types of symmetric equilibria across mandatory and voluntary settings and compare them in terms of participation, efficiency (expected welfare), and expected profits.

Our main results reveal several advantages of the voluntary setting. It yields weakly higher expected participation and weakly higher expected welfare compared to the mandatory setting. It also leads to weakly higher expected profits of participants, when the information costs are so high that in the mandatory setting potential bidders are excluded – a situation common in many real-world procurement auctions. The auctioneer may also benefit from the voluntary setting, but not to the same extent as the participants. While the auctioneer's expected profit can favor either setting depending on the parameters, the voluntary setting shows an advantage when information costs are high. High information costs are particularly realistic in public procurement auctions, such as RE auctions, where participants must invest in costly technical, environmental, and permitting assessments.

The model can be extended to incorporate risk aversion, a more realistic assumption about firms. In the risk-averse case, investors reduce their participation probability due to sunk costs and the risk of not winning the auction, while non-investors can price their risk through bids based on certainty equivalents. As a result, compared to the risk-neutral case, risk-averse non-investors tend to participate at higher reserve prices, but with a relative advantage over risk-averse investors due to their ability to account for uncertainty. Further, the mixed investment behavior can be alternatively interpreted as partial investment, leading to probabilistic information revelation. A potential extension for future research is to explicitly model partial information revelation, allowing for a reduction but not complete elimination of cost uncertainty.

While the analytical comparison generally favors the voluntary setting, especially under high information costs, these results are based on theoretical benchmarks. A key limitation of our model lies in the assumption that the auction outcome is binding, i.e., the auction winner will certainly realize the project. In practice, however, the non-realization risk is a concern, particularly for non-investors, when ex-post realized costs exceed expectations. We leave this for future research.

Chapter 3

Designing Renewable Energy Auctions for High Realization Probability – CfD and Payment-only Auctions

3.1 Introduction

Since the competitive allocation – typically by auctions – of rights for the construction and operation of RE plants began more than 10 years ago, different forms of auctions have been discussed and implemented (e.g., Anatolitis et al., 2022). In recent years, RE auctions have polarized between two trends: toward two-sided contract for difference (CfD)s, which serve as a hedging instrument for electricity sales, and toward payment-only auctions, where electricity sales remain unregulated and auction winners make payments to the auctioneer. The latter has become particularly established for offshore wind. The tension between these two trends became particularly apparent after the German offshore wind auction in 2023 (e.g., Ehrhart et al., 2024b). In this auction, two winners submitted unexpectedly high payment bids of 12.6 billion euros for the leases of four wind sites with a combined capacity of 7 gigawatt (GW). This result prompted stronger calls for two-sided CfDs, as the payment-only auction was seen to drive excessive bidding competition, increase financing costs, and put pressure on supply chains (e.g., BDEW, 2025; WindEurope, 2024). Even the European Commission has expressed its support for CfDs (Commission, 2023b; European Parliament and Council, 2024). Against this background, the increased non-realization risk of awarded projects has also been emphasized, along with how CfDs could mitigate this risk.

The risk that RE projects not being realized is a key issue, as it could jeopardize politically determined RE expansion targets. This is particularly relevant for offshore wind: If the decision not to proceed with the project is made several years after the auction, it can cause delays of many years and may require the auctioneer to schedule a new auction for the site. Such delays result in welfare losses that can be reflected in the value of foregone greenhouse gas emission reductions (based on the price of emission allowances), higher electricity prices, sunk costs, health impacts, and other factors. While much of the literature emphasizes the benefits of integrating RE into power systems (e.g., Lynch and Curtis, 2016; Koecklin et al., 2021), these benefits also underscore the opportunity costs in case of delayed realization. Using hypothetical projects, Longoria et al. (2024) show that without delay, wholesale electricity prices could be up to 10% lower in a given year, and CO_2 emissions up to 3.4% lower. Moreover, Shawhan et al. (2025), using simulations, demonstrate that delays in clean energy infrastructure hinder RE deployment, prolong fossil fuel use, and generate billions of dollars in annual welfare losses through higher emissions, health damages, and inequitable burdens on low-income households. This is further backed by empirical evidence. A Lawrence Berkeley National Laboratory survey (Nilson et al., 2024) finds that roughly one-third of U.S. wind and solar projects were canceled and half experienced delays of six months or more; cancellations led to average non-recoverable sunk costs of over $2 million per solar project and $7.5 million per wind project, and delays cost around $200,000 per MW.

A CfD is a financial agreement in which a buyer and a seller settle the difference between a pre-agreed strike price and the market price of an underlying asset at the time of delivery. In electricity markets, CfDs are long-term contracts between an electricity generator and the government, with payments linked to the actual electricity produced or the reference energy quantity (see Section 3.2, Schlecht et al., 2024). CfDs are particularly useful when developers cannot realize projects solely with expected revenues from the electricity market and thus require government support. In this case, a CfD strike price (hereafter referred to as “CfD price”) above the expected electricity price contributes to the expansion of RE. When projects are viable without government support, CfDs are still argued to reduce risks for developers, thereby supporting cost-effective and reliable RE expansion (e.g., Neuhoff et al., 2022; Fabra, 2023; Khodadai and Poudineh, 2024; Đukan et al., 2025). In line with this, CfDs are associated by their advocates with a higher realization probability, especially for risk-averse developers (e.g., Neuhoff et al., 2022). Although many studies highlight the advantages of CfDs, their disadvantages are often understated or even overlooked, which include the decoupling of the electricity market and potential barriers to market integration (e.g., Schlecht et al., 2024). While developments such as financial CfDs address some of these weaknesses, these new CfD types have their own weaknesses (see Section 3.2.2).

Another often overlooked aspect is that CfDs are typically determined through auctions. In a CfD-allocating auction (hereafter referred to as a “CfD auction”), the bidder(s) with the lowest bid(s) win. It can be assumed that a developer who is willing to pay a high amount to the government in a payment-only auction (hereafter referred to as a “payment auction”) would submit a low bid in a CfD-allocating auction, possibly even much lower than the expected electricity price (see Section 3.6.1 for an example). CfDs should therefore not be regarded as a pure support instrument but rather as a hedging instrument, since the total net payment can flow in either direction – from the government to the developer or vice versa. Consequently, arguments in favor of CfDs, particularly regarding higher realization probability, should not be assessed in isolation but rather in relative comparison with payment auctions under the same conditions. This is where our analysis comes in: focusing on the non-realization risk, we compare a CfD auction with a payment auction under the same conditions. These conditions include the same bidders with the same projects as well as the same uncertainty regarding investment costs. Our model incorporates private investment cost of developers, overlaid with common investment cost uncertainty. In addition, the payment auction involves uncertainty regarding the electricity market prices (i.e., market revenue), since the auction winner participates in the unregulated electricity market (market solution, also called merchant), whereas CfDs hedge against market price risk. Besides, developers' private investment costs may vary further between the two auctions due to different financing conditions and other factors.

Theoretical models typically assume that actors are either risk-neutral or risk-averse, with risk aversion being more common in analyses of companies or investors. (e.g., Wüstenhagen and Teppo, 2006; Haering et al., 2020). This is also the case in analyses of the electricity market (e.g., Abate et al., 2022; Möbius et al., 2023). Risk aversion is implicitly assumed that bidders in payment auctions add a risk premium to their bids compared to bids for CfDs (see Section 3.2, e.g. Neuhoff et al., 2022; Khodadai and Poudineh, 2024). In policy debates, advocates of CfDs point to their role in reducing non-realization risk (i.e., increasing realization probability), arguing that risk-averse developers benefit from the reduced electricity price risk due to CfDs (e.g., Neuhoff et al., 2022). However, our results contradict this argument: We show that CfD auctions are not superior to payment auctions in terms of project realization. When projects are viable without government support, the non-realization risk is in fact higher for a CfD auction than for a payment auction under risk neutrality, and this effect is enforced by risk aversion. At the first glance, these results appear somewhat paradoxical, since CfDs hedge market price risk, which would normally benefit risk-averse developers. As our analysis shows, CfDs induce more aggressive bidding behavior of risk-averse bidders due to their derisking effect, which implies less “bidding buffer” against cost uncertainty compared to payment auctions and thereby lowering realization probability (see Section 3.4).

Based on our analysis and observations of RE auctions and the development of relevant markets, we also examine whether it would be advisable to allow participating developers to decide whether to allocate a CfD in the auction. This idea is supported by asymmetric information, i.e., developers know more about the factors that determine the value of a project than the auctioneer, particularly under the constantly changing conditions in recent years. To this end, we propose a mechanism in which developers competitively choose between a CfD auction and a payment auction, thereby achieving a high realization probability. This mechanism prioritizes payment auctions where feasible, while providing CfDs when required for offshore wind expansion.

The remainder of this chapter is structured as follows. Section 3.2 discusses different forms of support and hedging instruments and the payment auction. Section 3.3 lays the foundation for the theoretical analysis in Section 3.4, followed by model extensions in Section 3.5. Section 3.6 presents practical examples that highlight weaknesses of the selected auction designs. Section 3.7 propose a mechanism to address these weaknesses. Section 3.8 concludes with policy recommendations. Proofs of the lemmas, propositions and corollaries are provided in Appendix B.

3.2 Support and hedging instruments and the payment auction

This section briefly describe different forms of support and hedging instruments and the payment auction, which form the basis of the auction-theoretic analysis in Section 3.4.

3.2.1 One-sided floating FIP (oFIP) and traditional CfD (tCfD)

The main support and hedging instruments for RE projects are directly linked to the amount of energy fed into the grid and take the form of a subsidy per unit of energy, kWh or MWh (e.g., Gephart et al., 2017). A central class of instruments is CfDs, also known as FIPs (e.g., Anatolitis et al., 2022). Two variants are commonly distinguished: the one-sided floating feed-in-premium (oFIP) and the two-sided traditional contract for difference (tCfD).[1] Both forms require operators to sell the energy they generate on the electricity market.[2] Payments to or from the operator are determined as the difference between a fixed premium and a reference price derived from the electricity price, e.g., the monthly average of the so-called technology specific market value (e.g., Hirth, 2013). Under a oFIP, if the reference price is lower than the premium, the operator receives the difference between the premium and the reference price for the quantity marketed; if the reference price is higher than the premium, no payment is made. A tCfD provides the same downside protection, but differs in that the operator must pay the difference back when the reference price is higher than the premium.

[1] The oFIP is also referred to as the one-sided CfD. The tCfD is also known as the two-sided floating FIP. For clarity and better differentiation, this thesis consistently uses the abbreviations oFIP and tCfD.

[2] The operator of a project is typically also its developer. In the following, both terms are used synonymously. The term operator is more common in the context of selling energy on the market, whereas developer is more frequently used in the context of auctions (where they are also referred to as bidders) and project implementation.

Consequently, by definition, while oFIPs function both as a support and a hedging instrument, tCfDs are a hedging instrument rather than a support instrument. Both oFIPs and tCfDs protect the operator from low electricity prices. While oFIPs allow the operator to keep the excess revenue above the premium, tCfDs require the excess revenue to be paid to the government. Due to this design difference, the operator's indifference price – the award price at which the operator is indifferent about winning the auction or not – is higher for the tCfD than for the oFIP and thus also the bid prices and award prices.

In recent years, the scope of the application of tCfDs have steadily increased (AURES II, 2022; Schlecht et al., 2024). This is also related to a forward-looking reform of the electricity markets (Fabra, 2023). An overview of the advantages associated with tCfDs is provided by Neuhoff et al. (2022). One of the main advantages of tCfDs over the oFIP and particularly over the payment auction (see Section 3.2.3) is that they reduce the developers' uncertainty regarding future revenue by eliminating exposure to electricity price risk. CfDs thereby lower financing costs for developers. This, in turn, reduces the overall cost of RE procurement and provides consumers with more stable prices (e.g., Steffen and Waidelich, 2022; Fabra, 2023; Kröger et al., 2022; Gohdes et al., 2022). Moreover, due to the absence of electricity price risk, it is also claimed that CfDs generally offer better protection against the non-realization risk than the oFIP or the market solution (e.g., May et al., 2018; Kell et al., 2022; Neuhoff et al., 2022; Stiftung Offshore Windenergie, 2025).

Despite these advantages, tCfDs have some drawbacks, especially as their prevalence increases with an increasing share of RE installations. These drawbacks relate to induced investment, production, and market distortions (Schlecht et al., 2024). One of the biggest weaknesses is the lack of incentive for market integration, which contradicts the European Commission guidelines that explicitly require the integration of RE into the electricity market.[3] Under a tCfD, operators are incentivized to maximize output as long as the electricity price is positive. In other words, they do not have an incentive to act in a market-consistent way, i.e., to adapt production to market conditions by producing more (less) at high (low) prices (e.g., Khodadai and Poudineh, 2024). This discourages investments in system-friendly RE facilities that smooth the RE generation profile with its typical fluctuations. Because the tCfDs dampen fluctuations in the electricity market, they also distort its scarcity signals, which increase as the share of CfD-hedged plants increases. This leads to distorted decisions about plant maintenance, retrofitting and renewal.[4]

[3]Commission (2018, Article 4): (2) "Support schemes for electricity from RE sources shall provide incentives for the integration of electricity from renewable sources in the electricity market in a market-based and market-responsive way, while avoiding unnecessary distortions of electricity markets as well as taking into account possible system integration costs and grid stability." (3) "Support schemes for electricity from renewable sources shall be designed so as to maximize the integration of electricity from renewable sources in the electricity market and to ensure that RE producers are responding to market price signals and maximize their market revenues."

[4]A variant of the tCfD that may mitigate this problem is to define a corridor (with lower and upper limits)

oFIPs, in comparison, provide stronger incentives for market-compliant behavior and thus allowing a better integration of RE into the market. While a tCfD price must remain positive, at least in the long term, the oFIP price can be zero. This was first observed in an RE auction for offshore wind in Germany in 2017 (BNetzA, 2017). oFIP price at zero is equivalent to the market solution with zero payment (Section 3.2.3). The main criticisms of oFIPs are based on this. Their structure causes bidders to either forgo hedging, exposing themselves completely to market price risk, and benefit fully from possible high electricity market prices. Due to the negligible variable costs of RE, critics view high profits from high electricity prices as undesirable windfall profits (e.g., Khodadai and Poudineh, 2024). Consequently, oFIPs are being phased out in practice. The European Commission explicitly supports the use of CfDs in these contexts.[5]

Finally, both oFIPs and tCfDs shift electricity price risks from the operators to the government, eventually to the public. This raises the political debate of how risks can or should be distributed within society (Beiter et al., 2024). This aspect is more relevant for tCfDs because, when determined competitively, a tCfD price will be higher than a oFIP price.

3.2.2 Financial CfD

To address the weaknesses of the tCfD, the so-called financial contract for difference (fCfD) has been proposed. The fCfD combines the conventional tCfD with incentivized electricity marketing (Newbery, 2023; Schlecht et al., 2024). Its basic principle is to separate the two components of the hedge from the production and marketing of electricity. For this reason, the fCfD is also referred to as a production-independent CfD. A reference energy quantity is derived individually from the capacity of a plant, to which the fCfD is applied. If the market reference price is lower than the CfD price, the operator receives a payment equal to the price difference multiplied by the reference energy quantity. Conversely, if the market reference price is higher than the CfD price, the operator has to make the corresponding payment to the auctioneer. Operators can sell the energy they actually produced on the electricity market without any restrictions. Since they cannot influence the payments to or from the auctioneer during the operating period, they are incentivized to align their sales behavior with market conditions. As a result, the scarcity signals in the market are not disturbed, operators have an incentive to follow them, and market integration is promoted.

within which the CfD does not apply, but only for reference prices below the lower limit and above the upper limit. However, this concept raises new questions about how to set the lower and upper limits and whether it undermines the idea behind CfDs.

[5]Recital (35) of European Parliament and Council (2024): “Where Member States decide to support publicly financed investment by direct price support schemes in new low carbon, non-fossil fuel power-generating facilities to achieve the Union’s decarbonization objectives, those schemes should be structured as two-way contracts for difference or equivalent schemes with the same effects such as to include, in addition to a revenue guarantee, an upward limitation of the market revenues of the generation assets concerned.”

The main advantages of fCfDs over tCfDs are that fCfDs incentivize operators to participate in the electricity market as "normal" suppliers and that fCfDs allocate risks to the parties that can best handle them (Schlecht et al., 2024). Specifically, electricity price and weather risks are shifted from operators to the public.[6]

However, this works effectively only if the reference energy volume closely reflects the actual production. Since perfect accuracy of the reference energy quantity cannot be guaranteed, a new type of uncertainty arises, the so-called basis risk. Basis risk occurs when the reference quantity is misaligned with the actual production, which could lead to high payments from the operator. For instance, if the reference quantity is fixed, the operator has to make high payments during periods of high electricity prices caused by supply shortages, such as poor wind conditions, even though the plant produces hardly any marketable electricity. In such cases, the operator may be worse off than under a tCfD. To avoid this, the reference energy volume must be adapted to match the actual production conditions of a plant. However, this is not only complicated and costly, but also means that the production independence of the concept and the associated positive effects are partially lost.

Another critical consideration is that the fCfD may create incentives for operators to optimize plant design to exploit the determination of the reference quantity. This is because deviations between actual and reference energy quantities are unavoidable, partly due to the excessive effort required for greater accuracy. The fCfD may even encourage the development of installations specifically tailored to this purpose. The creativity of market participants in this regard should not be underestimated. Such incentives can conflict with the objective of efficient, system-friendly energy production. This implies that support or hedging schemes should be designed as simply as possible because each additional rule or adjusting screw increases the risk of creating uncontrollable and undesirable incentives.

3.2.3 Payment auction

Since the first occurrence of zero-cent bids in a oFIP auction (see Section 3.2.1), many countries have switched to auctions in which auction winners do not receive support or hedging but instead must make a payment to the auctioneer. In our model, we refer to these as negative payments for consistency. Therefore, the auctions award the lowest payment bids (see Section 3.3.1). Auction winners participate in the electricity market and can decide whether to equip themselves with privately negotiated hedges, such as PPA or offshore renewable energy credit (OREC).[7] This is also referred to as the market solution. Payment auctions, for example, are used for offshore wind in Germany, the US, and the UK (EEG, 2023; BOEM, 2022; Crown Estate, 2025).

[6]As with tCfDs, this raises the political issue of risk distribution (Beiter et al., 2024).

[7]Similar to tCfDs, both PPA and OREC contracts set a fixed price for the supply of energy services (e.g., Jansen et al., 2022).

3.3 Framework and setup of the analysis

The analysis compares auction designs for RE that eliminate electricity price risk for bidders with those that do not. For this purpose, the term CfD is used to cover the concepts tCfD and fCfD without distinguishing between them, as both concepts share the principle of excluding electricity price risk. The comparison focuses on the realization probability. The decision whether to implement a project (i.e. realization) becomes relevant, if the auction winner receives information after the auction indicating that the project's economic viability is lower than expected. In such cases, the decision then depends on penalties for non-realization.

3.3.1 Two scenarios

We consider two scenarios, C and N. Scenario C covers all types of CfDs that fully eliminate the electricity price risk. This applies to tCfD and fCfD discussed in Section 3.2. In the auction in C, bidders submit bids indicating the CfD price. The bidder with the lowest bids wins. Scenario N refers to payment auctions with electricity price risk (i.e., no hedging or support). The bidder with the lowest bid wins. The payment auction (i.e., the market solution) in Section 3.2.3 is captured by only allowing non-positive bids in N. To enable a general comparison with C, we also permit positive bids in N that represent a one-time payment from the auctioneer to the developers, which correspond to lump sum capex subsidies. The submitted bids determine whether a payment is made to or from the auctioneer, depending on whether the bids are negative or positive. We assume this initially so that all bidders can participate in N in any case. The case in which positive bids are not feasible in N is discussed in Section 3.7.[8]

If winning bidders fail to implement the project in C or N, they must pay a penalty, for example by forfeiting a bid bond, which must be submitted before the auction. Bidders who did not win receive their bond back after the auction.

3.3.2 Timeline and uncertainties

Figure 3.1 illustrates the timeline of the whole process on which the analysis in Section 3.4 is based. As assumed in Section 3.3.1, all bidders have an incentive to participate in either auction. First, the auction is conducted among all participants. This is followed by the implementation decision period, which typically lasts up to a few years. During this period, the winning bidder must decide whether to implement (realize) the project. If the project is implemented, the operating period starts. Our analysis focuses on the pre-operation phases.

There are two categories of uncertainty in different periods. The first category includes

[8]Positive bids in N can also be simplified as bids for a oFIP (Section 3.2.1) if it is assumed that their change has only a minor impact on market price uncertainty for the bidders.

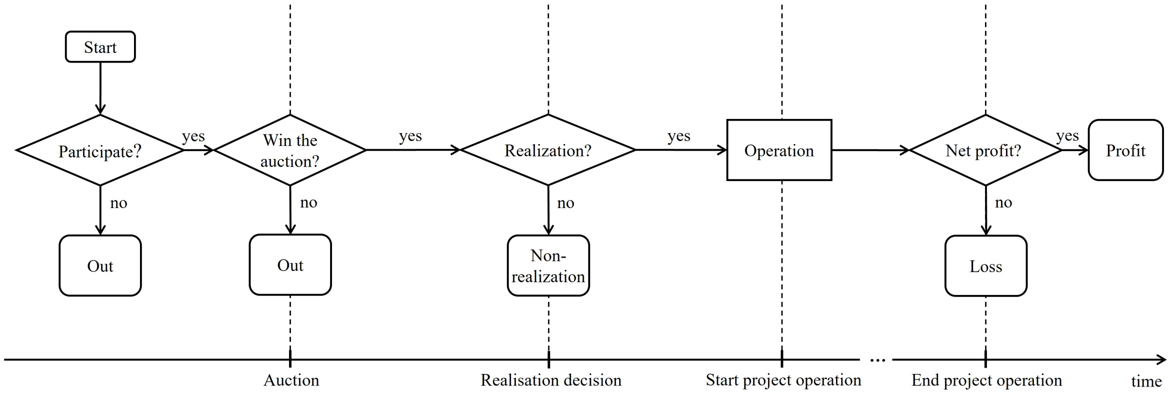

Figure 3.1: Timeline of the whole process

uncertainties that developers face regarding material and installation costs, administrative processes (e.g., obtaining permits), environmental factors, and other installation-related issues (cost uncertainty). These uncertainties exist at the time of the auction and are resolved during the implementation decision period when information about the uncertain factors is revealed. This applies equally to C and N. The non-realization risk refers to the implementation decision period: If the winning bidder learns during this period that the project's value is lower than initially expected, non-realization may occur, depending on the severity of the deviation and penalties. The second category refers to uncertainties about electricity price and generated quantities (revenue uncertainty). In N, these uncertainties fully apply to the market solution. In C, we assume that these uncertainties are fully excluded in C.[9] Thus, these uncertainties only become relevant in N once the plant is operational. If the winning bidder discovers during the operational period that the project's value is lower than expected, the winning bidder will likely incur an unavoidable loss. Figure 3.2 in Section 3.4 illustrates the evolution of information and uncertainty over the entire timeline.

Given the timeline, uncertainties in the first category are more relevant for non-realization risk, as they materialize during the implementation decision period (the post-auction shock). While new information about uncertainties in the second category (e.g., electricity price expectations) may also emerge in this period, these uncertainties unfold over the long operational period in the future. We therefore disregard such updates in the first step of our analysis and focus solely on resolved uncertainties in the first category. In a second step, we account for updated information on uncertainties in the second category during the implementation decision period (see Section 3.5.1).

[9] The volume risk only applies to the tCfD, while fCfDs involve the so-called basis risk (Section 3.2.2).

3.4 Basic model

Consider n a priori symmetric bidders, $n \geq 2$, each with wealth w and the von Neumann-Morgenstern utility function u. We consider cases in which all bidders are risk-averse, risk-neutral or, for the sake of completeness, risk-seeking.[10]

Bidders are characterized by private cost signals $\theta_i \in [\underline{\theta}, \bar{\theta}]$, which are realizations of n independent and identically distributed random variables Θ_i with the distribution function F and density function f. f is assumed to be log-concave.[11] For simplicity, we omit the index i for Θ. In scenario C, each bidder i's private costs are equal to θ_i, i.e., $\theta_i^C = \theta_i, \forall i \in \{1, ..., n\}$. The private costs of the bidders in scenario N differ from that in C by a parameter τ. This accounts for additional costs incurred due to the higher uncertainty in N caused by revenue uncertainty. For example, a positive τ accounts for higher financing costs in N (see Section 3.2.1). Assuming that the bidders are subject to different conditions relevant in N, such as internal or external financing, τ may vary among bidders (e.g., Kröger et al., 2022; Gohdes et al., 2022). This is modeled by the random variable $\mathcal{T}$, which is independent of Θ. Thus, in scenario N, $\Theta^N = \Theta + \mathcal{T}$. For simplicity, we assume there are two types of realization of $\mathcal{T}$: τ_h with probability ϱ and τ_ℓ with probability $1 - \varrho$, $\tau_h > \tau_\ell$.[12] Although higher financing costs are a common assumption, we allow $\mathcal{T}$ to be negative. Bidder i's private costs at the time of the auction are $\theta_i^N = \theta_i + \tau_i$, $\tau_i \in \{\tau_\ell, \tau_h\}$. Let $\Theta_{(k)}$ and $\Theta_{(k)}^N$ denote the k-th order statistics of the random variables of the private cost signals Θ and Θ^N.

At the time of the auction, there is common uncertainty regarding the investment costs (first category of uncertainty). This uncertainty is related to factors that affect all bidders equally, such as material or installation costs. This is modeled by the random variable Y with the distribution function G and density function g on the support $[\underline{y}, \bar{y}]$, and $\mathbb{E}[Y] = 0$. Y is a "post-auction shock" and realizes y in the implementation decision period.[13] Therefore, the a priori implementation costs of each bidder are $\Theta + Y$ in C and $\Theta^N + Y$ in N. Bidder i's implementation costs at the time of the auction are $\theta_i^C + Y$ in C and $\theta_i^N + Y$ in N. We assume that the common cost uncertainty is significant compared to the variation of the private costs, which is captured by the assumption std.dev$(Y) \geq$ std.dev(Θ).

The future revenue in C is a constant, which is determined by the award price from the

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[10]For the risk-averse bidders, we assume a non-increasing Arrow-Pratt measure of absolute risk aversion. The Arrow-Pratt measure of absolute risk aversion is defined as $-u''/u'$ (Arrow, 1971). If this measure is non-increasing, the risk premium of a risky investment decreases in the wealth level (Pratt, 1978; Kimball, 1993; Mas-Colell et al., 1995).

[11]A density function f is log-concave on the support Ω if, for any $x_1, x_2 \in \Omega$ and $\varrho \in [0, 1]$, $f(\varrho x_1 + (1-\varrho)x_2) \geq f(x_1)^\varrho f(x_1)^{1-\varrho}$ (e.g., An, 1998). Many common probability distributions are log-concave, e.g., normal distribution, exponential distribution, or uniform distribution (e.g., Bagnoli and Bergstrom, 2005).

[12]Our results would be the same if $\mathcal{T}$ were continuously distributed on $[\underline{\tau}, \bar{\tau}]$. Then there would be a cutoff τ^*, such that all $\tau \leq \tau^*$ would be considered as low τ, and all $\tau > \tau^*$ would be considered as high τ. The same applies when assuming that $\mathcal{T}$ and Θ are positively correlated.

[13]Until then, the approach corresponds to that of Board (2007), for example.

CfD auction. In N, the future revenue is modeled by the random variable Z (second category of uncertainty) with distribution function H and density function h on the support $[\underline{z}, \bar{z}]$. Random variable Z realizes z in the operation period. For a basic comparison of the two scenarios, we assume that this uncertainty is the same for all bidders in N. Private hedging instruments such as PPAs and their possible differences are not taken into account.

The distributions of all random variables Θ, $\mathcal{T}$, Y and Z are common knowledge. For simplicity's sake, we omit the discounting of monetary values, which is not restrictive when assuming a uniform discount rate for all bidders. We also assume that the CfD is effective throughout the entire operating period.

Consider a representative bidder i. For simplicity, we omit the index i. Let b_C^* and b_N^* denote the bidder's indifference bids under scenarios C and N, respectively. At the indifference bids, the bidder is indifferent between winning and not winning the auction, i.e., the expected utility from winning the auction equals the utility of the current wealth $u(w)$. In second-price auctions (including English auctions), bidding the indifference price is a weakly dominant strategy. Suppose that if the bidder wins, the bidder gets the award price p_C or p_N, determined by the next best bidder, where $p_C \geq b_C^*$ and $p_N \geq b_N^*$. In scenario C, only the first uncertainty category is relevant, so the bidder's utility from implementation is $u(w + p_C - \theta - Y)$. In scenario N, both uncertainty categories are relevant, so the bidder's utility from implementation is $u(w + p_N - \theta - \tau - Y + Z)$. In the basic model, we assume that Z is not updated during the implementation decision period (see Section 3.5.1 for a model extension). Information, uncertainties, and cash flows throughout the whole process are illustrated in Figure 3.2.

In both scenarios, if the project is not implemented (non-realization), the bidder must pay a penalty $s \geq 0$, where $w \geq s$ ensuring the bidder can cover the penalty. The bidder's ex-ante expected utility conditional on winning at the award price p_C or p_N in both scenarios are given by

$$U_C(p_C) = \int_{\underline{y}}^{y_C^*(p_C)} u(w + p_C - \theta - y)g(y)dy + \int_{y_C^*(p_C)}^{\bar{y}} u(w - s)g(y)dy, \tag{3.1}$$

$$U_N(p_N) = \int_{\underline{y}}^{y_N^*(p_N)} \int_{\underline{z}}^{\bar{z}} u(w + p_N - \theta - \tau - y + z)h(z)dzg(y)dy + \int_{y_N^*(p_N)}^{\bar{y}} u(w - s)g(y)dy, \tag{3.2}$$

where $y_C^*(p_C)$ and $y_N^*(p_N)$ denote the threshold of the realization of Y (hereafter referred to as the implementation cost threshold), at which the bidder is indifferent as to whether or not to implement the project, depending on the award prices p_C or p_N. Thus, the probability that the project will be implemented is given by $G(y_C^*(p_C))$ or $G(y_N^*(p_N))$ and increases in $y_C^*(p_C)$

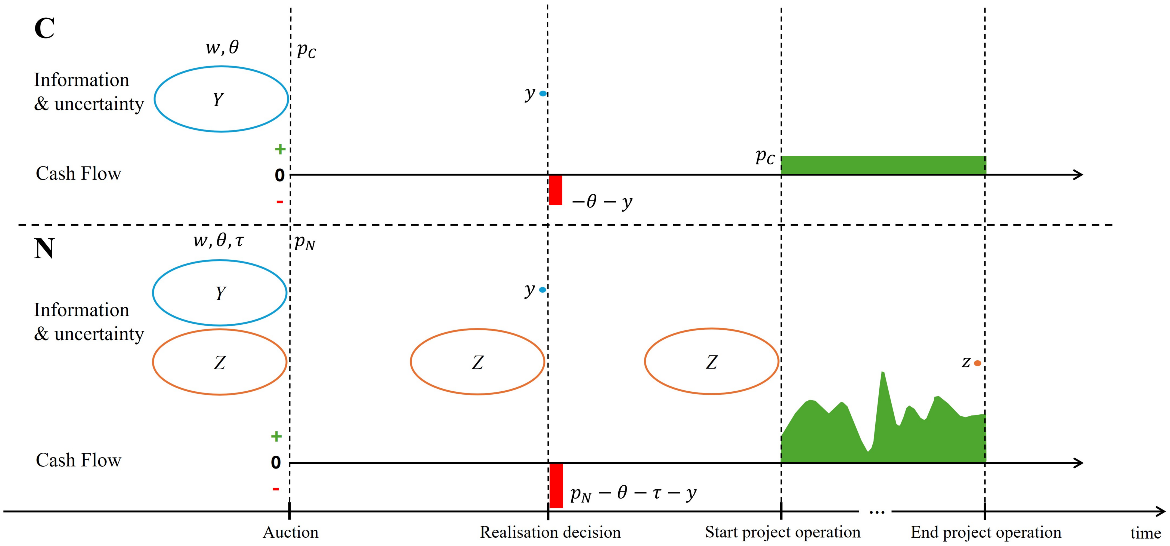

Figure 3.2: Information, uncertainty, and cash flow over the entire timeline for of an exemplary auction winner under realization in scenarios C and N

or $y_N^*(p_N)$. The implementation cost thresholds are determined by equating the bidder's (expected) utility from implementation at the given award price and the utility from paying the penalty s:

$$u(w + p_C - \theta - y_C^*(p_C)) = u(w - s), \tag{3.3}$$

$$\int_{\underline{z}}^{\bar{z}} u(w + p_N - \theta - \tau - y_N^*(p_N) + z)h(z)dz = u(w - s). \tag{3.4}$$

After y is realized, the winner will implement the project if and only if y does not exceed the corresponding threshold.

At the indifference bids b_C^* and b_N^*, we have

$$U_C(b_C^*) = U_N(b_N^*) = u(w), \tag{3.5}$$

$$u(w + b_C^* - \theta - y_C^*(b_C^*)) = u(w - s), \tag{3.6}$$

$$\int_{\underline{z}}^{\bar{z}} u(w + b_N^* - \theta - \tau - y_N^*(b_N^*) + z)h(z)dz = u(w - s). \tag{3.7}$$

Due to their different references, the indifference bids b_C^* and b_N^* cannot be compared directly. Instead, the expected electricity market revenues and the cost parameter τ in N must also be taken into account, so that b_C^* and $b_N^* + \mathbb{E}[Z] - \tau$ can be compared.

Lemma 6. *The following relationships hold for different risk preferences:*

- *Risk-averse bidders:* $b_C^* < b_N^* + \mathbb{E}[Z] - \tau$ *and* $y_C^*(b_C^*) < y_N^*(b_N^*)$
- *Risk-neutral bidders:* $b_C^* = b_N^* + \mathbb{E}[Z] - \tau$ *and* $y_C^*(b_C^*) = y_N^*(b_N^*)$
- *Risk-seeking bidders:* $b_C^* > b_N^* + \mathbb{E}[Z] - \tau$ *and* $y_C^*(b_C^*) > y_N^*(b_N^*)$

Under risk neutrality, b_C^* and $b_N^* + \mathbb{E}[Z] - \tau$ are equal for C and N as are $y_C^*(b_C^*)$ and $y_N^*(b_N^*)$ and thus also the realization probability at the indifference bids b_C^* and b_N^*. This changes once bidders exhibit non-neutral risk preferences. For risk-averse bidders, $b_C^* < b_N^* + E[Z] - \tau$ indicates a more aggressive indifference bid in C, and $y_C^*(b_C^*) < y_N^*(b_N^*)$ indicates a lower realization probability in C at the indifference bid. This result arises because scenario C eliminates more risk than scenario N. Consequently, risk-averse bidders require a higher risk premium in scenario N to compensate for the additional uncertainty, resulting in a higher expected revenue at the same expected utility level. Furthermore, since the implementation costs threshold is positively correlated with the indifference price, the threshold at the indifference bid is higher in N than in C. This implies a higher realization probability in scenario N. The opposite holds for risk-seeking bidders. Since both scenarios involve risk, they require a negative risk premium in both scenarios, where the risk-premium is lower (more negative) in N due to the additional uncertainty in Z. This results in a lower indifference bid and a lower realization probability at the indifference bid in N.

Consider now two bidders with the same utility function u, Bidder i with θ_i and τ_i, and Bidder j with θ_j and τ_j. We use the subscripts C, N, i, and j to denote indifference prices and implementation costs thresholds, referring to the respective scenarios and bidders.

Lemma 7. *For any two bidders i and j, it holds that* $b_{C,j}^* - b_{C,i}^* = \theta_j^C - \theta_i^C$ *and* $y_{C,j}^*(b_{C,j}^*) = y_{C,i}^*(b_{C,i}^*)$*;* $b_{N,j}^* - b_{N,i}^* = \theta_j^N - \theta_i^N$ *and* $y_{N,j}^*(b_{N,j}^*) = y_{N,i}^*(b_{N,i}^*)$*.*

Lemma 7 states that the difference between the indifference bids of any two bidders exactly equals the difference of their private costs in each scenario, i.e., $\Delta\theta = \theta_j^C - \theta_i^C$ in C and $\Delta\theta^N = \theta_j^N - \theta_i^N$ in N. As a result, in the equilibrium with weakly dominant strategy, bidders' indifference bids increase monotonically in their private cost in the respective auction. Consequently, the bidder with the lowest θ^C wins in C, whereas the bidder with the lowest θ^N wins in N, which may lead to different winners due to the independence between $\mathcal{T}$ and Θ. This result holds for any two bidders with the same utility function, regardless of what that risk preference is. Besides, the realization probability at each bidder's own indifference price is the same across all bidders. This is because at the implementation costs threshold, all bidders have the same expected utility, and bidders with higher private cost take this into account and price this into their indifference price accordingly.

Lemma 8. *For any two bidders i and j, it holds that* $y^*_{C,i}(b^*_{C,j}) = y^*_{C,i}(b^*_{C,i}) + \theta^C_j - \theta^C_i$ *and* $y^*_{N,i}(b^*_{N,j}) = y^*_{N,i}(b^*_{N,i}) + \theta^N_j - \theta^N_i$.

If a bidder wins the auction at an award price higher than its own indifference bid, whereby this award price is determined by a higher indifference bid of another bidder, the realization probability increases relative to that at its own indifference bid. Lemma 8 shows that this increase is exactly equal to the difference in their private costs $\Delta\theta$ and $\Delta\theta^N$. This result holds in both scenarios C and N regardless of bidders' risk preferences.

Due to the additional dispersion from $\mathcal{T}$, the expected difference in private cost between the price setter and the winner is larger in N than in C.

Lemma 9. $\mathbb{E}[\Theta^N_{(2)}] - \mathbb{E}[\Theta^N_{(1)}] \geq \mathbb{E}[\Theta_{(2)}] - \mathbb{E}[\Theta_{(1)}]$.

Regarding the realization probability, the following holds.

Proposition 8. *If all bidders are either risk-averse or risk-neutral, each with either* τ_ℓ *or* τ_h*, the auctioneer expects higher realization probability in* N *than in* C*. If all bidders are risk-seeking, the result is ambiguous.*

According to Lemma 9, the winner in N benefits in expectation more from the additional dispersion introduced by different τ. Therefore, from the auctioneer's perspective, scenario N yields a higher realization probability and is therefore preferred.

At the same time, with risk-averse bidders, scenario N leads to a higher expected award price. Thus, from a revenue-maximizing or cost-minimizing perspective, the auctioneer would instead prefer scenario C over N. Note that the objectives of maximizing revenue (or minimizing cost) and achieving a higher realization probability conflict with each other and thus cannot be achieved simultaneously. In this chapter, the primary objective of the auctioneer is to achieve a high realization probability and thereby promote the targeted expansion of RE (see Section 1.2).

Now let's take the perspective of the bidders. For risk-neutral bidders, according to Lemma 6 and 8, the expected utility conditional on winning at prices p_C and p_N are equal, i.e., $U_C(p_C) = U_N(p_N)$ if and only if $p_C - b^*_C = p_N - b^*_N$. For risk-averse or risk-seeking bidders, this is ambiguous and depends on the specific form of the utility function.[14] However, the impact of the utility function is very small, mainly because the uncertain price p_C and p_N

[14]Under the rather unrealistic assumption that $u''' < 0$ ($u''' > 0$), it holds that $\frac{\partial U_C(p_C)}{\partial \Delta\theta} > (<) \frac{\partial U_N(p_N)}{\partial \Delta\theta}$, where $\Delta\theta = \theta_j - \theta_i$ and $U_C(p_C) = U_N(p_N)$ if $\Delta\theta = 0$. Therefore, we have $U_C(p_C) > U_N(p_N)$ ($U_C(p_C) < U_N(p_N)$.). However, under the more realistic assumption that $u''' > 0$ ($u''' < 0$), the comparison becomes unclear and requires additional assumptions.

only slightly exceeds the bid b_C^* and b_N^* in comparison to the uncertainty caused by Y. For this reason, we assume equivalence for all forms of risk preference.

Assumption 1. *$U_C(p_C) \gtreqless U_N(p_N)$ iff $p_C - b_C^* \gtreqless p_N - b_N^*$.*

Let $EU_C(b_C^*)$ and $EU_N(b_N^*)$ denote the expected utilities, accounting for the wining probability. It follows that

$$EU_C(b_C^*) = \int_{b_C^*}^{\bar{b}_C} U_C(p_C) f_C(p_C) dp_C + F_C(b_C^*) u(w),$$
$$EU_N(b_N^*) = \int_{b_N^*}^{\bar{b}_N} U_N(p_N) f_N(p_N) dp_N + F_N(b_N^*) u(w).$$

The density functions f_C and f_N correspond to the distribution functions F_C and F_N. The expressions $1 - F_C(b_C^*)$ and $1 - F_N(b_N^*)$ denote the winning probabilities of the bidder with indifference bids b_C^* and b_N^* in C and N, respectively. For C, it holds that $1 - F_C(b_C^*) = (1 - F(\theta))^{n-1}$. The upper bounds $\bar{b}_C$ and $\bar{b}_N$ denote the maximum prices in both scenarios. Since our model does not initially implement an upper limit, $\bar{b}_C$ and $\bar{b}_N$ are set to infinity (see Section 3.7 for finite maximum prices). As a result, following (3.5), $EU_C(b_C^*) \geq u(w)$ and $EU_N(b_N^*) \geq u(w)$ for all b_C^* and b_N^*, so all bidders have an incentive to participate in either auctions, regardless of their private costs.

Assume that Assumption 1 applies. The following applies to the winning probability, the expected utility, and the realization probability in C and N.

Proposition 9. *If all bidders are either risk-averse or risk-neutral, then the following holds:*

- *For bidders with τ_ℓ: $1-F_C(b_C^*) < 1-F_N(b_N^*)$, $\mathbb{E}[y_C^*(P_C)] < \mathbb{E}[y_N^*(P_N)]$, and $EU_C(b_C^*) < EU_N(b_N^*)$.*
- *For bidders with τ_h: $1 - F_C(b_C^*) > 1 - F_N(b_N^*)$, $EU_C(b_C^*) > EU_N(b_N^*)$, and, for risk-neutral bidders, $\mathbb{E}[y_C^*(P_C)] > \mathbb{E}[y_N^*(P_N)]$.*

That is, regardless of risk preference, bidders with τ_ℓ prefer N while bidders with τ_h prefer C. It is the relative level of τ, not its absolute value, that determines this preference. Lower τ increases both the winning and realization probability in N relative to C, while higher τ has the opposite effect.

In our model, it is assumed that bidders have the same beliefs about cost and revenue uncertainty (modeled by Y and Z with distribution functions G and H, which are common knowledge). Bidders are differentiated by their private costs. In the absence of a common prior, such as when some bidders are more optimistic than others, this can be captured in a common-value model in which bidders have different signals regarding uncertainties (e.g., Milgrom and Weber, 1982). Assuming the same risk preference, May et al. (2018) argue that the market solution favors the most optimistic bidder with regard to revenue uncertainty, thereby reducing the probability of project realization. This is because downward revisions of price expectations after the auction can result in cancellations despite penalties. Our approach, however, does not yield the same conclusion. Since revenue uncertainty Z is not resolved at the time of the implementation decision, optimism or pessimism regarding revenue uncertainty has no impact on the implementation decision. By contrast, an optimistic prior regarding cost uncertainty can indeed reduce the realization probability, an effect that applies equally to both scenarios C and N (with the opposite effect for pessimism). In other words, despite different prior beliefs, our main result that the expected realization probability is higher in N than in C for either risk-averse or risk-neutral bidders, remain unchanged.

The following can be stated with regard to efficiency. The auctions in C and N are incentive compatible, i.e., bidders submit their indifference bids, which, as assumed, are not limited by maximum prices. Therefore, each of the two auctions in C and N is efficient when viewed separately. This changes when the two actions are considered together. Since the τ differs between the bidders in N, there may be different winners in N and C, with the probability of a winner with τ_ℓ in N being higher than that of a winner with τ_h. According to Proposition 8, the realization probability in N is higher than in C in case of risk-neutral or risk-averse bidders. Thus, if $\tau_\ell > 0$, as argued, no statement about efficiency can be made without further specifications. Even if $\tau_\ell \leq 0$, there is no clear result, although the probability of the efficient outcome in N is higher than in C. If $\tau_h \leq 0$, the N auction is the efficient one. For risk-seeking bidders, the results are ambiguous. On the one hand, the bids in N are relatively higher than in C, which reduces the realization probability. On the other hand, the bids in N are more widely scattered than in C, which increases the realization probability. Therefore, as in the previous case, the model must be specified in more detail in order to make a clear statement about efficiency.

3.5 Model extensions

This section presents extensions to the basic model in Section 3.4.

3.5.1 Information update during the implementation decision period

Suppose that the distribution of Z is updated during the implementation decision period. At the time of the implementation decision, the bidder faces the random variable Z_1 with distribution function H_1 and density h_1, which is a update of Z with H and h. The implementation costs threshold in scenario C remains unchanged, as Z plays no role in C.

The updated threshold in scenario N, denoted with $\hat{y}_N^*$, is determined by

$$\begin{aligned}&\int_{\underline{z}}^{\bar{z}} u(w + p_N - \theta - \tau - y_N^*(p_N) + z)h(z)dz \\ =&u(w - s) = \int_{\underline{z}}^{\bar{z}} u(w + p_N - \theta - \tau - \hat{y}_N^* + z)h_1(z)dz.\end{aligned}$$

For the update, we consider first-order stochastic dominance in both directions: $Z_1 \succ_1 Z$ and $Z \succ_1 Z_1$. That is, the update improves or worsens the beliefs about electricity revenues. If bidders are risk-averse or risk-neutral, according to Proposition 8, the auctioneer expects that $y_N^*(p_N) > y_C^*(p_C)$. If $Z_1 \succ_1 Z$, then it follows that $\hat{y}_N^* > y_N^*(p_N)$. Consequently, the realization probability is expected to be higher in N than in C, and the difference becomes even larger than in the basis model with Z in Section 3.4. Thus, the advantage of N is reinforced. This result already holds under the weaker condition of second-order stochastic dominance, $Z_1 \succ_2 Z$ (Rothschild and Stiglitz, 1970). This includes the case that Z_1 is a mean preserving contraction of Z, i.e., $\mathbb{E}[Z] = \mathbb{E}[Z_1]$, but Z_1 exhibits less dispersion around the mean. Such a case reflects the situation in which bidders receive updated information about the future electricity market, which reduces uncertainty regarding future revenue. The decrease in uncertainty raises the expected utility of the risk-averse bidder and thereby increases the realization probability in scenario N. In contrast, if $Z \succ_1 Z_1$, then $\hat{y}_N^* < y_N^*(p_N)$. However, no general statement can be made with respect to the realization probability of C and N, because it is expected to be higher for N under Z in the basis model (Corollary 1). Thus, the advantage of N over C weakens and may reverse.

Shifting the distribution Z by a constant Δz in either direction, without changing its shape, i.e., $h_1(z + \Delta z) = h(z), \forall z \in [\underline{z}, \bar{z}]$, is a special case of first-order stochastic dominance: $\Delta z > 0 \Leftrightarrow Z_1 \succ_1 Z$ and $\Delta z < 0 \Leftrightarrow Z \succ_1 Z_1$. The indifference equation becomes

$$\begin{aligned}&\int_{\underline{z}}^{\bar{z}} u(w + p_N - \theta - \tau - y_N^*(p_N) + z)h(z)dz \\ =&\int_{\underline{z}+\Delta z}^{\bar{z}+\Delta z} u(w + p_N - \theta - \tau - \hat{y}_N^* + x)h_1(x)dx \\ =&\int_{\underline{z}}^{\bar{z}} u(w + p_N - \theta - \tau - \hat{y}_N^* + z + \Delta z)h(z)dz.\end{aligned}$$

Consequently, $\hat{y}_N^* = y_N^*(p_N) + \Delta z$. According to Lemma 8, define $\Delta y^* := y_N^*(p_N) - y_C^*(p_C) = \Delta\theta^N - \Delta\theta$. It follows that $\hat{y}_N^* \geq y_C^*(p_C) \Leftrightarrow \Delta z \geq -\Delta y^*$.

If bidders are risk-neutral or risk-averse, Proposition 8 implies $\Delta y^* > 0$. Therefore, if $\Delta z \geq 0$, i.e., the bidder's beliefs about future revenue improves during the implementation decision period, then the realization probability is expected to be higher in N than in C. This also applies if the bidder's beliefs worsen only to the extent that the shift does not exceed

Δy^*, i.e., $\Delta z \geq -\Delta y^*$. Only if $\Delta z < -\Delta y^*$, the realization probability in N falls below that in C. In other words, bidders in N effectively "insure" against unfavorable belief updates by bidding more "conservatively" and thus expecting higher revenue upfront. This conservatism creates a buffer Δy^*, which protects the implementation decision against moderate negative belief updates.

If bidders are risk-seeking, since no general relationship can be established between $y_N^*(p_N)$ and $y_C^*(p_C)$, no general statement can be made between $\hat{y}_N^*$ and $y_C^*(p_C)$. In principle, regardless of risk preference of the bidders, $Z_1 \succ_1 Z$ – including the special case $\Delta z \geq 0$ – improves the realization probability in N relative to than in C than in the basic model, while the reverse holds for $Z \succ_1 Z_1$ or $\Delta z < 0$.

3.5.2 Payment auction with payment before the implementation decision

The following considerations apply only to the usual case in practice, where only negative bids can be submitted in the N auction, meaning that the winning bidders must make a payment to the auctioneer (see also Section 3.6). Therefore, only bidders with a negative indifference bid participate, i.e., those with $b_N^* \leq 0$.[15] This is only feasible if the project is expected to be profitable without support.

Now consider the case in which a part of the payment is due before the implementation decision. This reflects, for instance, the payment requirement in current U.S. offshore wind auctions (BOEM, 2018; BOEM, 2022) and the 10% payment due within the first year after the auction in the current German offshore wind auction (WindSeeG, 2023, §23). Denote by $\delta, \delta \in (0,1]$, the proportion of the payment that dues before the implementation decision. This payment is not reimbursed if the auction winner decides not to realize the project. Equation (3.5) then extends to

$$U_N(b_N^*) = \int_{\underline{y}}^{y_N^*(b_N^*)} \int_{\underline{z}}^{\bar{z}} u(w + b_N^* - \theta - \tau - y + z)h(z)dzg(y)dy + \int_{y_N^*(b_N^*)}^{\bar{y}} u(w - s + \delta b_N^*)g(y)dy = u(w).$$

Compared to Equation (3.5), the second term now contains the additional negative component δb_N^*. To satisfy $U_N(b_N^*) = u(w)$, both the indifference bid b_N^* and the corresponding threshold $y_N^*(b_N^*)$ must increase relative to the basic model. That is, $|b_N^*|$ becomes smaller, reflecting more conservative bidding behavior. Consequently, in the equilibrium, the award price, denoted by p_N^b, is higher, i.e., $p_N < p_N^b \leq 0$.[16]

At the time of the implementation decision, this early payment is a sunk cost for the

[15] We assume that the bidders' wealth level w is sufficient to cover the payment when due. Otherwise, w imposes an upper bound on the negative bid, resulting in a higher expected utility and thus a higher realization probability than at b_N^*.

[16] This presupposes that the new, higher indifference bid is also negative. Otherwise, the bidder would not participate in the auction. Therefore, early payment increases the risk of general non-participation and failure of the auction.

winning bidder and thus should not be relevant for the implementation decision. Equation (3.4) becomes

$$\int_{\underline{z}}^{\bar{z}} u(w + (1-\delta)p_N^b - \theta - \tau - y_N^*(p_N) + z)h(z)dz = u(w - s).$$

Since $(1-\delta)p_N^b > p_N$, the threshold $y_N^*(p_N)$ increases compared to the basic model. Since the project is profitable itself, bidders are willing to sacrifice part of their expected market revenue to win the auction. This sacrificed portion makes the project less profitable. If this sacrificed portion is paid before the implementation decision and becomes sunk, the project implementation is more attractive, thus raising the realization probability. The larger the portion of the early payment, the more attractive the project at the time of the implementation decision, and thus the higher the realization probability, while this must be weighed against potential higher financial costs of early payment.

In summary, requiring payments before the implementation decision can increase realization probability in N, thus contributing to efficiency and welfare. This result holds regardless of the bidders' risk preference. However, this effect is only beneficial as long as the associated additional financial costs do not outweigh the gains in implementation incentives. Additionally, the early payment approach can create financial issues for developers if the project proves to be significantly more expensive than expected after payment has been made. Nevertheless, the project will be carried out due to sunk costs, which would not have been the case with a later payment. Furthermore, a higher proportion of early payment increases the risk of non-participation if only negative payment bids are permitted. Under the mechanism proposed in Section 3.7, however, this adverse effect no longer arises.

3.5.3 Comparison of bidders with different risk preferences

Now, consider the comparison of bidders with different risk preferences: a risk-averse bidder, a risk-neutral bidder, and a risk-seeking bidder. For comparison, the three bidders have the same private costs θ^C and θ^N. The superscripts RA, RN, and RS indicate the different risk types. The utility function of the risk-neutral bidder is linear, so we set $u^{RN}(x) = x$. Additionally, we normalize the wealth level such that $u^{RN}(w) = w = u^{RA}(w) = u^{RS}(w)$. The indifference bids are denoted by b_k^{RS}, b_k^{RN}, and b_k^{RA}, $k = C, N$.

Proposition 10. *It holds that $b_C^{RS} < b_C^{RN} < b_C^{RA}$ and $b_N^{RS} < b_N^{RN} < b_N^{RA}$. Additionally, it holds that $b_C^{RA} - b_C^{RN} < b_N^{RA} - b_N^{RN}$, $b_C^{RA} - b_C^{RS} < b_N^{RA} - b_N^{RS}$, and $b_C^{RN} - b_C^{RS} < b_N^{RN} - b_N^{RS}$.*

Proposition 10 implies that the less risk-tolerant a bidder is, the higher the indifference bid. This is because a risk-averse bidder demands a risk premium to compensate for uncertainty (captured by Y in scenario C and by both Y and Z in scenario N), whereas a risk-neutral bidder does not. As a result, the risk-averse bidder submits the highest bid. By contrast, a risk-seeking bidder accepts a risk discount, which results in the lowest indifference bid. Moreover, the difference in indifference bids between risk-averse and risk-neutral bidders is larger in N than in C. That is, the risk-neutral bidder has a greater competitive advantage relative to the risk-averse bidder with the same private cost in N. This is because scenario N involves greater exposure to risk, which is tolerated by the risk-neutral bidder but disliked by the risk-averse bidder. Analogously, this relationship generally holds between a less and a more risk-tolerant bidder.

Next, we compare hypothetical auctions that only differ in the risk preference of the winning bidder. Other bidders do not need to be specified in more detail. For this purpose, we fix the award price p_C in C and the award price p_N in N. Within this framework, we can compare realization probabilities across different risk preferences within each auction format (C or N), but not between them.

Proposition 11. *At the price p_C or p_N, it holds that $y_C^{RS}(p_C) = y_C^{RN}(p_C) = y_C^{RA}(p_C)$ and $y_N^{RS}(p_N) > y_N^{RN}(p_N) > y_N^{RA}(p_N)$.*

Proposition 11 shows that the realization probability is identical across different risk preferences in C, since no uncertainty remains at the time of the implementation decision (after y is realized). In contrast, in scenario N, where uncertainty from the electricity market persists at the time of the implementation decision, the realization probability increases with risk tolerance: It is highest for the risk-seeking auction winner, followed by the risk-neutral auction winner, and lowest for the risk-averse auction winner. This is because the upper limit of the actual implementation costs, up to which a bidder will realize the project, is higher for a risk-seeking bidder than for less risk-tolerant bidders.

In summary, a risk-neutral bidder has a competitive advantage over a risk-averse bidder with the same private cost in terms of higher winning probability in both scenarios C and N, regardless of the risk preferences of other bidders. Their advantage is further reinforced in N due to greater risk tolerance. Risk-seeking bidders perform even better because they are willing to bid even more aggressively and accept greater risk. Besides, given a fixed award price, the auctioneer would prefer the winner to be less risk-averse, since more risk-tolerant bidders exhibit a higher realization probability. Therefore, from the auctioneer's perspective, a more risk-tolerant bidder is, ceteris paribus, a more desirable auction participant in terms of both competitive intensity and implementation success.

3.5.4 Model with constant cost difference between C and N

As a special case, suppose that the cost difference between C and N is constant and the same for all bidders, i.e., $\tau_\ell = \tau_h = \tau$. As a result, the bidder with the lowest θ wins in both C

and N, and the price setter, whose indifference bid sets the award price in either auction, is the bidder with the second lowest θ. Therefore, Lemma 6 can be extended to the auction outcome.

Corollary 1. *Assume that Bidder i wins the auction in C or in N at prices p_C or p_N, where $p_C = b^*_{C,j}$ and $p_N = b^*_{N,j}$ are the indifference bids of Bidder j with θ_j, $\theta_j \geq \theta_i$. The following relationships hold for different risk preferences:*

- *Risk-averse bidders: $p_C < p_N + \mathbb{E}[Z] - \tau$ and $y^*_{C,i}(p_C) < y^*_{N,i}(p_N)$.*
- *Risk-neutral bidders: $p_C = p_N + \mathbb{E}[Z] - \tau$ and $y^*_{C,i}(p_C) = y^*_{N,i}(p_N)$.*
- *Risk-seeking bidders: $p_C > p_N + \mathbb{E}[Z] - \tau$ and $y^*_{C,i}(p_C) > y^*_{N,i}(p_N)$.*

Under risk neutrality, p^*_C and $p^*_N + \mathbb{E}[Z] - \tau$ are equal for C and N as are $y^*_C(p_C)$ and $y^*_N(p_N)$ and thus the realization probabilities, i.e., $G(y^*_C(p_C)) = G(y^*_N(p_N))$. Since risk-averse (risk-seeking) bidders require a higher (lower) risk premium in N than in C, this leads to relatively higher (lower) price in N and thus a larger (smaller) bidding buffer against the uncertainty of Y.[17] As a result, risk-averse (risk-seeking) bidders face a lower (higher) non-realization risk in N.

Since the auctions in C and N are incentive compatible, they are efficient when viewed separately. When the two actions are considered together, the same bidder wins both the C and N auction and the award price in N differs by τ from that in C. Thus, if $\tau > 0$, the C auction is the efficient one for risk-neutral and risk-seeking bidders; if $\tau < 0$, the N auction is the efficient one for risk-neutral and risk-averse bidders. For risk-averse bidders with $\tau > 0$ or risk-seeking bidders with $\tau < 0$, no general statement can be made.

Bidders with mixed risk preferences Given constant τ, consider now bidders with mixed risk preferences in the same auction.[18] We consider the two prevailing forms of risk neutrality and risk aversion, assuming that there are two types of bidders: risk-avers bidders with the same utility function u^{RA} and risk-neutral bidders with u^{RN}. This mixture is common knowledge and risk preference is independent of θ. In both scenarios C and N, the lowest bid wins and the second-lowest bid determines the price, regardless of risk preferences of the corresponding bidders.

Proposition 12. *If bidders have mixed risk preferences, then for risk-averse bidders it holds that $EU_C(b^*_C) \geq EU_N(b^*_N)$; for risk-neutral bidders it holds that $EU_C(b^*_C) \leq EU_N(b^*_N)$.*

[17] A higher p_N is favorable to the auction winner, implying a higher payment from the auctioneer to the auction winner if p_N is positive, or a lower payment from the auction winner to the auctioneer if p_N is negative.

[18] There is evidence from market and experimental studies that risk preferences can differ between actors (e.g., Walters et al., 2023; Ren et al., 2024; Hey and Orme, 1994; Deck and Schlesinger, 2014).

Proposition 12 states that risk-averse bidders weakly prefer the CfD auction while risk-neutral bidders weakly prefer the payment auction. Note that with bidders with mixed risk-preferences, the equation $1 - F_C(b_C^*) = 1 - F_N(b_N^*) = (1 - F(\theta))^{n-1}$ does not hold anymore. Rather, as stated in Proposition 10, risk-neutral bidders have a greater competitive advantage over risk-averse bidders and thus a higher winning probability in scenario N, given the same private cost, i.e., $1 - F_C(b_C^*) < 1 - F_N(b_N^*)$. Besides, the expected utility in winning case is higher in N than in C for risk-neutral bidders. Consequently, risk-neutral bidders prefer N to C. Conversely, risk-averse bidders prefer C.

Bidders with different wealth level Now consider two bidders with the same θ, τ, and u but different wealth w_i and w_j, assume that $w_i \geq w_j$ without loss of generality.

Proposition 13. *For any two bidders i and j with $w_i \geq w_j$, the following relationships hold:*

- *For risk-neutral bidders: $b_{C,i}^{RN} = b_{C,j}^{RN}$ and $y_{C,i}^{RN}(b_{C,i}^{RN}) = y_{C,j}^{RN}(b_{C,j}^{RN})$; $b_{N,i}^{RN} = b_{N,j}^{RN}$ and $y_{N,i}^{RN}(b_{N,i}^{RN}) = y_{N,j}^{RN}(b_{N,j}^{RN})$.*
- *For risk-averse bidders with non-decreasing Arrow-Pratt measure of absolute risk aversion, no general statement can be made.*
- *For risk-seeking bidders with $u''' > 0$: $b_{C,i}^{RS} < b_{C,j}^{RS}$ and $y_{C,i}^{RS}(b_{C,i}^{RS}) < y_{C,j}^{RS}(b_{C,j}^{RS})$; $b_{N,i}^{RS} < b_{N,j}^{RS}$ and $y_{N,i}^{RS}(b_{N,i}^{RS}) < y_{N,j}^{RS}(b_{N,j}^{RS})$.*

Proposition 13 implies that the wealth level has no effect on the indifference bids of risk-neutral bidders. While under the assumption of a non-increasing Arrow-Pratt measure of absolute risk aversion, no general statement can be made for risk-averse bidders, a higher wealth level leads to higher indifference bids and thus higher realization probabilities at the own indifference bids for risk-seeking bidders in both scenarios C and N, given that $u''' > 0$. The assumption of u''' implies that risk-seeking bidders become more risk-seeking as wealth increases.[19] In summary, when considering the effects of wealth level, the absolute level of risk preference at each wealth level plays an important role.

Proposition 14. *For any two bidders i and j with $w_i \geq w_j$, and the auction price p_C or p_N, the following relationships hold:*

- *For risk-neutral bidders: $y_{C,i}^{RN}(p_C) = y_{C,j}^{RN}(p_C)$ and $y_{N,i}^{RN}(p_N) = y_{N,j}^{RN}(p_N)$.*
- *For risk-averse bidders: $y_{C,i}^{RA}(p_C) = y_{C,j}^{RA}(p_C)$ and with non-decreasing Arrow-Pratt measure of absolute risk aversion, no general statement can be made for scenario N.*

[19] If we allow $u'''(x) < 0$ for risk-averse bidders, i.e., risk-averse bidders become more risk-averse as wealth increases, then a higher wealth level leads to lower indifference bids and thus lower realization probabilities at the own indifference bids for risk-averse bidders in both scenarios C and N.

- *For risk-seeking bidders:* $y^{RS}_{C,i}(p_C) = y^{RS}_{C,j}(p_C)$ *and with* $u''' > 0$, $y^{RS}_{N,i}(p_N) < y^{RS}_{N,j}(p_N)$.

In scenario C, there is no uncertainty at the time of the implementation decision. According to Equation (3.3), it holds that $y^*_C(p_C) = p_C - \theta + s$, which is independent of w. Thus, the implementation decision is independent of risk preference and wealth level. In scenario N, on the contrary, both risk preference and wealth level are essential for the implementation decision. For risk-neutral bidders, the wealth level has again no effect on the realization probability. While under the assumption of a non-increasing Arrow-Pratt measure of absolute risk aversion, no general statement can be made for risk-averse bidders, assuming $u''' > 0$ a higher wealth level leads to higher realization probability at the same award price for risk-seeking bidders.[20] Again, when considering the effects of wealth level, the absolute level of risk preference at each wealth level plays an important role.

Pay-as-bid (PaB) pricing Consider now PaB pricing. Due to the penalty $s > 0$ and positive non-realization risk, the revenue equivalence theorem does not apply (see e.g., Kreiss et al., 2017a; Parlane, 2003; Board, 2007). This holds both for model with different and constant τ. A counter example for the model with constant τ can be found in Appendix B.2.

3.6 Implementation in practice

In the model in Section 3.4, all bidders can participate in the auctions in scenarios C and N. In C, this is achieved by allowing unrestricted CfD bids. This is not usually the case in practice. Instead, an effective maximum bid price is set that excludes less profitable projects. In N, participation is achieved by allowing negative and unrestricted positive bids, through which bidders determine whether they will make a payment to the auctioneer or receive a payment from the auctioneer. The latter corresponds to an investment subsidy. In practice, however, this option is usually not available; only the option of a payment to the auctioneer is available.

In this framework, the auctioneer has two options: to allocate a CfD in an auction with a maximum price (scenario C); or to receive a payment from the winning bidder in an auction, which only allows negative bids, i.e., payments from the bidders to the auctioneer (scenario N). So far, with one exception (see Section 3.6.2), the auctioneer has decided in advance on one of the two options C or N. Section 3.6.1 contains examples of auctions that have led to undesirable results in this regard.

[20] Similarly, if we allow $u'''(x) < 0$ for risk-averse bidders, then a higher wealth level leads to lower realization probabilities at the same award price for risk-averse bidders in scenario N.

3.6.1 Examples

At the 2021 Danish offshore wind CfD auction, several zero cents bids were submitted, so the winner was determined by lottery (Danish Energy Agency, 2021). To understand this, it is important to note that the CfD was only valid for three and a half years. After that, a free market regime applies. This result indicates the attractiveness of the location and the conditions, as the developers were willing to forgo income during the CfD period. However, the auction was deemed unsuccessful. First, drawing the winner through a lottery is associated with the risk of inefficiency. Second, the concept of a CfD as a support and hedging instrument has lost its intended meaning. Nevertheless, this example shows that intense competition for a CfD is to be expected when conditions are favorable, leading to low or even zero prices.

This event was apparently at least partly responsible for Denmark's switch to payment auctions. Since these only permit negative bids, i.e., bidders can only make payments to the auctioneer and not vice versa, they no longer have the option of receiving support. The Danish December 2024 auction for 3 GW of capacity did not attract any bidders, so the planned early 2025 auction for an additional 3 GW was suspended (Memija, 2024; Memija, 2025). The main reason was that procurement conditions had worsened for developers. Factors inhibiting them include higher inflation, rising interest rates, supply chain bottlenecks, expected low electricity prices, a lack of market opportunities, and uncertainties in the electricity market (e.g., Turner et al., 2024). Another factor was that the auction winners had to pay for the grid connection. Apparently, the projects required electricity sales revenue that exceeds market expectations. However, this could not be achieved through a payment auction.

The same happened in Germany in 2025 at the auction for two centrally pre-investigated offshore wind sites. In this multi-attribute auction with a payment component, no bids were submitted (BNetzA, 2025b).

In 2025, the UK put three offshore wind sites, each for a capacity of 1.5 GW, out to tender in a payment auction. However, only two sites were awarded because no bids were submitted for the third sites (Crown Estate, 2025). This case is also interesting because the auction winners have the opportunity to obtain a CfD in a later CfD auction. The payment auction and the CfD auction should be evaluated in together. The rule that sites must first be auctioned and paid before a developer can apply for support creates additional uncertainty and risks for developers, which could discourage them from participating.[21]

[21]In the UK, CfD auctions are held annually for various technologies, including offshore wind energy. Technologically specific maximum bid prices apply in the these auctions. After no bids were submitted for offshore wind energy in 2023 (e.g., New Energy World, 2023), the maximum price was raised for subsequent auctions in 2024 and 2025 (GOV.UK, 2025).

3.6.2 Design for combining oFIP and payment

The aforementioned problems could be avoided by using an auction design that includes both elements, support and payment. Such an approach is currently used in Germany to allocate non-centrally pre-investigated offshore wind sites (WindSeeG, 2023, §16 et seqq.).[22] This two-stage design combines a oFIP auction and a payment auction. In the first stage, each bidder submits a bid for a oFIP in a simultaneous first-price auction. If no more than one bidder submits a zero-cent per kWh bid in the first stage, the bidder with the lowest bid wins the auction and receives a oFIP equal to the bid. If at least two bidders offer zero cents per kWh in the first stage, indicating their expectation to manage the project without a oFIP, a payment auction will take place. All zero-cent bidders from the first stage can participate in this payment auction. In the payment auction, bidders offer a payment with their bid for the site. The bidder with the lowest bid (largest payment amount) wins the auction and has to pay the bid. This means that if conditions are such that no bidder expects to be able to manage without support, then there will be support via oFIP. On the other hand, if at least one bidder believes the project can be managed without support, the market solution applies instead. To date, seven sites in Germany have been put out to tender under this procedure in 2023-25, each of which was competitively allocated in the second stage through the payment auction (BNetzA, 2025a).

3.7 Design proposal

The examples in Section 3.6.1 show that the auctioneer's decision to use either CfD or payment may not be suitable. In this regard, one of the main arguments in favor of auctions emerges, namely asymmetric information (e.g., Klemperer, 1999). This means that the bidders have a better knowledge of the factors determining the project value than the auctioneer does. One solution to this problem is to allow the bidders to decide competitively whether or not they need support, as is the case in the design in Section 3.6.2.

This section proposes a design for combining CfD and payment, as described in the first paragraph of Section 3.6: a CfD auction with a maximum bid price, and a payment auction in which only negative bids are permitted. If the oFIP is to be replaced by a CfD, the design in Section 3.6.2 must be adjusted to ensure proper functionality with CfD and negative payments. Unlike a oFIP, a CfD caps revenues. A negative payment is not a negative CfD; rather, it is an alternative below a certain CfD threshold. That is, there exists a payment that a bidder is willing to make instead of a CfD. Therefore, a different procedure is required, in which bidders choose between the CfD and the payment.[23]

[22] To our knowledge, this is still the only application worldwide of the combination of a support and a payment auction in the context of RE.

[23] We do not pursue concepts that would result in a combination of a CfD and a negative payment, but only

The following presents such a mechanism in which the market solution is prioritized. The CfD solution should only be implemented if all bidders prefer it.

Definition 1. *Mechanism $\mathcal{M}$ consists of two alternative bidding processes: one for a CfD and one for a non-positive payment.*

The bidders simultaneously submit their bids. A CfD bid, b_C, may not be negative and may not exceed the maximum price $\bar{b}_C$: $0 \leq b_C \leq \bar{b}_C$. A payment bid, b_N, may not be positive: $b_N \leq 0 = \bar{b}_N$. Each bidder has four options:

1. *Submit only a CfD bid, b_C.*
2. *Submit both a CfD bid, b_C, and a payment bid, b_N.*
3. *Submit only a payment bid, b_N.*
4. *Submit no bid.*

If at least one bidder chooses the third option, the payment auction will take place. In this case, all bidders who submit a payment bid (second and third option) participate in this auction with their payment bids. If all bidders choose the fourth option, no auction will take place. In other cases, the CfD auction will take place, in which the bidders' CfD bids will then apply (first and second option).

In either auction, the bidder with the lowest bid wins. This bidder either receives a CfD at the second-lowest CfD bid or makes a payment equal to the second-lowest payment bid.[24]

The mechanism $\mathcal{M}$ implies that through the bid of the first option, the bidder indicates that they will only accept a CfD; through the bid of the second option, the bidder indicates that they prefer a CfD, but will accept the market solution; through the bid of the third option, the bidder indicates that they prefer the market solution. The mechanism $\mathcal{M}$ consistently considers all possible bidder preferences. Since only one bidder who prefers the market solution is sufficient to initiate it, the question of acceptance of the CfD in the case of a preference for the market solution does not need to be addressed.

The following applies to bidders with private cost signals (as described in Section 3.4), regardless of their risk preference.

Proposition 15. *The mechanism $\mathcal{M}$ is incentive compatible:*

1. *If $b_C^* \leq \bar{b}_C$ and $b_N^* > \bar{b}_N$, then $b_C = b_C^*$ and $b_N = \emptyset$.*

those that result in either a CfD or a payment. Reasons are that combined solutions are difficult to implement and monitor, and their benefits are questionable.

[24] If multiple bidders submit the winning bid, tie-breaking rules must be established. The options are to randomly select the winner or use the first-come, first-served time rule. If only one bidder participates, appropriate rules must be established. For example, the bidder could choose whether to receive a CfD at the maximum price $\bar{b}_C$ or accept the market solution without payment.

2. *If* $b_C^* \leq \bar{b}_C$ *and* $b_N^* \leq \bar{b}_N$ *and* $EU_C(b_C^*) > EU_N(b_N^*)$*, then* $b_C = b_C^*$ *and* $b_N = b_N^*$*.*

3. *If* $b_C^* \leq \bar{b}_C$ *and* $b_N^* \leq \bar{b}_N$ *and* $EU_C(b_C^*) \leq EU_N(b_N^*)$*, or if* $b_C^* > \bar{b}_C$ *and* $b_N^* \leq \bar{b}_N$*, then* $b_N = b_N^*$ *and* $b_C = \emptyset$*.*

4. *If* $b_C^* > \bar{b}_C$ *and* $b_N^* > \bar{b}_N$*, then* $b_C = \emptyset$ *and* $b_N = \emptyset$*.*

Proposition 15 states that it is optimal for each bidder to submit bid(s) truthfully based on two considerations: (i) whether the bidder accepts a CfD below the maximum price and/or the market solution, as determined by the relationship between their indifference bids and the respective maximum prices, and (ii) the preference between the CfD and the payment auctions. For either auction, if a bidder decides to participate, submitting the corresponding indifferent bid is a weakly dominant strategy, as in the basis model.

For the further analysis of $\mathcal{M}$, we use the basic model with different τ introduced in Section 3.4. We consider two cases of risk preferences: all bidders are risk-neutral or all bidders are risk-averse. According to Proposition 9, regardless of risk preference, a bidder with τ_ℓ prefers scenario N, while a bidder with τ_h prefers scenario C, provided the bidder is willing to participate in both auctions. Moreover, from the perspective of a bidder with τ_ℓ, the realization probability in N is greater than in C. These results also applies if $\bar{b}_N$ excludes more bidders than $\bar{b}_C$, provided that $\Delta\tau := \tau_h - \tau_\ell$ or n are sufficiently large (see the proof of Lemma 10 in Appendix B.3). Therefore, the following results hold independently of the bidders' risk preference.

Let $\hat{\theta}_{C,\ell}$, $\hat{\theta}_{C,h}$, $\hat{\theta}_{N,\ell}$ and $\hat{\theta}_{N,h}$ denote the cutoff costs for bidders in C and N with τ_ℓ and τ_h. The cutoff costs represent the values of θ at which the corresponding indifference bid equals the maximum bid, i.e., either $\bar{b}_C$ or $\bar{b}_N$. That is, if a bidder's private cost signal lies below (above) the corresponding cutoff cost, the bidder's indifference bid will be below (above) the maximum price, and the bidder will (not) participate in the corresponding auction. For instance, a bidder with τ_h and $\theta < \hat{\theta}_{N,h}$ satisfies $b_N^* < \bar{b}_N$ and thus participates in N. Therefore, the cutoff costs mark the upper limit of θ up to which bidders participate in the C auction or the N auction. This means that the higher the cutoff costs, the higher the expected number of bidders. Thus, higher cutoff costs indicate greater attractiveness of the auction. The cutoff costs depend on the utility function and τ and are monotone in the respective maximum bid. It holds that $\hat{\theta}_{C,\ell} = \hat{\theta}_{C,h} := \hat{\theta}_C$ and $\hat{\theta}_{N,h} = \hat{\theta}_{N,\ell} - \Delta\tau$, where $\Delta\tau = \tau_h - \tau_\ell > 0$. The cutoff costs do not need to be specified in more detail for the following analysis. In practice, while the market solution with $\bar{b}_N = 0$ may be challenging to implement depending on specific site and market conditions, the maximum CfD price is usually set generously to encourage participation.[25] Therefore, we assume that $\hat{\theta}_C > \hat{\theta}_{N,\ell} > \hat{\theta}_{N,h}$, i.e., a bidder who can cope with the market solution will also be able to do so with the maximum CfD price.[26]

[25] The case described in Footnote 21 could be considered a counterexample.

[26] Lemma 10 can be adapted to other possible relationships between the cutoff costs, where a bidder with

Lemma 10. *Consider the model with different τ, where each of the n bidders is independently and randomly assigned to τ_h with probability ϱ and to τ_ℓ with probability $1-\varrho$, for $\varrho \in [0,1]$. There are three possible outcomes of $\mathcal{M}$:*

(i) If there is at least one bidder with τ_ℓ such that $b_N^* \leq \bar{b}_N$, the payment auction takes place. The probability of this case is $1-[\varrho+(1-\varrho)(1-F(\hat{\theta}_{N,\ell}))]^n$.

(ii) If $b_C^* > \bar{b}_C$ and $b_N^* > \bar{b}_N$ for all bidders, then no bidder participates in either auction. The probability of this case is $(1-F(\hat{\theta}_C))^n$.

(iii) In all other cases, the CfD auction will take place. The probability is $[\varrho+(1-\varrho)(1-F(\hat{\theta}_{N,\ell}))]^n-(1-F(\hat{\theta}_C))^n$.

The probability of Case (i) increases in n and converges to 1 as $n \to \infty$, decreases in ϱ, and increases in $\hat{\theta}_{N,\ell}$. That is, stronger competition, a higher expected share of bidders with τ_ℓ, and greater attractiveness of the payment auction for bidders with τ_ℓ favor the payment auction. The probability of Case (ii) decreases in n and $\hat{\theta}_C$. Hence, the probability of no participation is high when competition is weak and the CfD maximum price offers insufficient attractiveness. The probability of Case (iii) benefits from less attractiveness of the payment auction for bidders with τ_ℓ and greater attractiveness of the CfD auction. If n is sufficiently large, then the probability of Case (iii) decreases in n and converges to 0 if $n \to \infty$. Note that $\hat{\theta}_{N,h}$ and thus $\Delta\tau$ does not influence the probabilities of any of the three cases.

The following numerical examples help to illustrate the underlying probability patterns: $\varrho = 50\%$, bidders' private cost signals are uniformly distributed on $[0,1]$, $n \in \{2,3,5,10\}$, $\hat{\theta}_C = 0.9 > \hat{\theta}_{N,\ell}$, and $\hat{\theta}_{N,\ell} \in \{0.25, 0.75\}$. We now compare the performance of $\mathcal{M}$ in terms of realization probability to that of the two individual auction formats, C and N.

Table 3.1: Probabilities of cases (i)–(iii) at different values of n and $\hat{\theta}_{N,\ell}$

$\hat{\theta}_{N,\ell}$	Case	$n=2$	$n=3$	$n=5$	$n=10$
	(i)	23,44%	33,01%	48,71%	73,69%
0.25	(ii)	1,00%	0,10%	$<0,01\%$	$\ll 0,01\%$
	(iii)	75,56%	66,89%	51,29%	26,31%
	(i)	60,94%	75,59%	90,46%	99,09%
0.75	(ii)	1,00%	0,10%	$<0,01\%$	$\ll 0,01\%$
	(iii)	38,06%	24,31%	9,54%	0,91%

$b_C^* > \bar{b}_C$ and $b_N^* \leq \bar{b}_N$ can also initiate the payment auction, leading to different probabilities. The proof and generalization of Lemma 10 are provided in Appendix B.3.

Proposition 16. *Mechanism $\mathcal{M}$ selects the auction with the weakly higher realization probability between C and N in most cases, except when no bidder with τ_ℓ satisfies $b_N^* \leq \bar{b}_N$ but at least one bidder with τ_h does.*

The exceptional case requires the bidders with τ_h to have significantly lower private cost signals θ_i – at least $\Delta\tau$ less – than bidders with τ_ℓ. The probability of this scenario is $[\varrho + (1-\varrho)(1-F(\hat{\theta}_{N,\ell}))]^n - [\varrho(1-F(\hat{\theta}_{N,\ell}-\Delta\tau)) + (1-\varrho)(1-F(\hat{\theta}_{N,\ell}))]^n$, which decreases in $\Delta\tau$, increases in ϱ, and converges to 0 if $n \to \infty$. For instance, $\varrho = 50\%$, bidders' private cost signals are uniformly distributed on $[0,1]$, $n = 5$, $\hat{\theta}_C = 0.9$, $\hat{\theta}_{N,\ell} = 0.75$, and $\hat{\theta}_{N,h} = 0.5$, the probability is 8.8%.

In conclusion, mechanism $\mathcal{M}$ positively contributes to welfare by combining bidders' knowledge of their support needs with the selection of solutions that increase the probability of project realization.

In the practice, mechanism $\mathcal{M}$ can be implemented alternatively as an equivalent two-stage mechanism with the payment auction in the first stage. This mechanism lets bidders reveal their preference competitively: first, bids are invited for the payment bid. If no bids are placed, the CfD option is opened. Silence signals a preference for a CfD, while bidders can still respond to others' payment bids. This avoids the strategic pressure to make overly optimistic forecasts about the market solution and prevents a prisoner's dilemma situation.

3.8 Policy implications and conclusion

The increasingly demanded CfDs are particularly advantageous for promoting the further expansion of RE if projects cannot be realized without support. In this context, CfDs can effectively promote participation and thus the expansion of RE. However, CfDs are not a panacea. Provided that developers can realize projects without support, we show that, despite various parties' claims to the contrary, CfDs allocated through auctions are disadvantageous in terms of project realization compared to a market solution without support. This is especially relevant for risk-averse bidders, who are often cited as a main argument in favor of CfDs. The advantage of the market solution over CfDs exists despite the additional financing costs associated with the market solution.

Therefore, focusing on high project realization probability, which is an essential aspect of the expansion of RE, we recommend to use CfDs only if developers cannot implement their projects without support, and to implement a market solution with payments by the auction winner, if possible. Due to information asymmetry – the developers have the best knowledge of the expected profitability of their planned project – the developers should decide competitively which of the two options to implement. This promises efficient solutions with low subsidy costs or high auction revenues. The argument of information asymmetry also implies that developers know best whether they need support to implement their project or not. A misjudgment by the auctioneer, as recently observed in several countries, can lead to undesirable outcomes such as a lack of participation and project delays. Therefore, our findings suggest that the goal of a high project implementation rate should be pursued by leaving the decision between CfD and market solutions to the developers. We present an auction design that meets this requirement. It invites developers to participate and almost always selects the solution with the highest realization probability.

Additionally, we recommend that the winning bidder in a payment auction make a partial payment to the auctioneer before the implementation decision is made. This is because an early payment increases the probability of realization, regardless of the bidders' risk preferences. The proportion or amount of early payments should be determined while taking into account potential adverse effects, such as higher financing costs and an increased risk of general non-participation.

Chapter 4

Combinatorial Auctions for Renewable Energy – Potentials and Challenges

4.1 Introduction

Most major economies have set a target of achieving climate neutrality by mid-century. The US has pledged to achieve 100% clean electricity by 2035 (US, 2021). The EU-level binding renewable energy (RE) target for 2030 has been raised to at least 42.5% (with an aspiration to 45%), up from 24.5% in 2023; many member states have set even higher targets for renewable electricity (Commission, 2023a; European Environment Agency, 2025; Ember, 2025). China aims to peak emissions before 2030 and to reach carbon neutrality by 2060. India targets around 500 GW of non-fossil capacity by 2030, and Japan sets an explicit target of at least 38% renewables in the power generation mix by 2030 (Ember, 2025). EU member states are obliged to implement competitive mechanisms to determine the support for RE (Commission, 2014; European Parliament and Council, 2018a; Commission, 2020). Auctions for RE support or for wind rights, which entail the right to construct and operate wind farms (Ausubel and Cramton, 2011), have become a commonly employed method to guide investments and promote the deployment of corresponding capacities (Szabó et al., 2020).

The successful utilization of auctions depends on several factors, including the selection of an appropriate auction design. This chapter focuses on the choice of auction design and presents application-specific policy recommendations regarding the use of combinatorial auctions (CAs) for RE. Our approach is in line with Liñeiro and Müsgens (2023), who consider auctions a flexible policy instrument that can be adapted to specific needs and situations, provided that policy makers have a deep understanding of their objectives and of how to translate them into effective design elements.

First, we discuss some basic properties of auctions. A key reason for using auctions is information asymmetry, i.e., the auctioneer is uncertain about the bidders' valuations of the auctioned items (e.g., Krishna, 2010, Ch.1). This applies in particular to the RE sector, where costs vary between bidders and differ in their structure: Some bidders have economies of scale, others do not, or even have diseconomies of scale due to budget or resource constraints. Typically, the auctioneer does not know the details, also because developers withhold information about their cost structures (Bichler et al., 2020). The auctioneer's uncertainty is reinforced by dynamic changes of individual technical parameters and costs as RE auctions are also designed to promote innovation (e.g., del Río et al., 2015b). Despite the auctioneer's uncertainty, a well-designed auction will allocate items according to the auctioneer's objectives. Identifying potential value or cost structures in qualitative terms helps to design the RE auction. Knowing them exactly is not necessary, rather the auction will reveal the relevant information. While uncertainty generally favors the use of auctions, the presence of both synergies and resource constraints, as well as the heterogeneity of RE developers in terms of their valuations and cost structures, are reasons to consider combinatorial auction (CA)s. CAs enable bidders to translate their different value and cost structures into bids in an appropriate and risk-free way. As a result, a CA can be designed to induce bidders to reveal their information and to support the auctioneer's objectives.

One main auctioneer objective is efficiency (e.g., Krishna, 2010, Ch.1), which is mandatory for RE auctions in the EU (European Parliament and Council, 2018b; Commission, 2021). An efficient outcome refers to achieving a given RE target at the lowest total cost to society (del Río et al., 2015b).[1] This requires the exploitation of synergy potential. Synergies in the RE sector arise from economies of scale or scope, which affect capex and opex. Capex includes costs for plants and foundations, installation costs and electrical infrastructure, and opex includes operating, logistics, administration and maintenance costs (Bichler et al., 2020; Kausche et al., 2018). Moreover, solar or wind farms can be configured more efficiently by selecting neighboring sites and benefiting from shared converter stations or grid connections. However, these cost components are difficult to quantify due to asymmetric information, heterogeneity, and different degrees of innovation. Therefore, little reliable data is available.

For offshore wind sites, Conradsen and Christensen (2020) analyze different opex cost categories and identify large potential cost savings due to synergy effects. For example, when two sites share operations, opex savings are 20–30% for maintenance or crew logistics costs and more than 30% for site organization operating costs. Combined with the fixed-bottom plant data in Stehly and Duffy (2022), this gives a reduction in the levelized cost of energy (LCOE)

[1] In the context of auctions, efficiency means maximizing total surplus conditional on all available information (Dasgupta and Maskin, 2000). That is, the developers with the lowest costs or the developers who assign the highest value to the auctioned items win.

of 7–10% or \$5–8 per MWh. Synergy effects were also responsible for some bidders in the 2017 auction in Germany (WindSeeG, 2023, §26 et seqq.) being able to forgo RE support and submit the world's first zero subsidy bids (e.g., EnBW, 2023). The result of the Borssele auction (see Section 4.4.3) also indicates the existence of synergies. Furthermore, Deutsche Windtechnik (2022) concludes that exploiting synergies significantly reduces maintenance-related downtime.

Synergy potential also exists for onshore technologies. However, these are usually more nuanced and more difficult to demonstrate than for offshore wind. Steffen et al. (2020) point to the existence of economies of scale through opex reduction for onshore technologies. In Dubai's 2014 solar auction, one developer incorporated synergies into its bids and presented a price-volume schedule where the bid price decreased as the project size increased (IRENA and CEM, 2015). The bid prices in \$ per MWh, as an indicator of the LCOE, decreased by 2.5% and 9.8%, respectively, due to the increase in capacity from 100 MW to 200 MW and from 200 MW to 1,000 MW.[2] Malaysia's large-scale solar auctions conducted between 2017 and 2021 saw differences in bid prices (in Malaysian ringgit (MYR) per kWh) for small and large installations of over 10% (IRENA, 2022). These examples show that synergies do exist.

CAs are particularly well suited when both synergies and substitutes are present (see sections 4.2.1 and 4.4.1), even if they cannot be quantified by the auctioneer. Especially in complex projects, such as hybrid projects (e.g., IEA, 2022; SoEnergieV, 2022; EEG, 2023, §39n), which are gaining in importance, synergies and other value and cost structures are difficult to identify or even quantify from the outside. Moreover, substitute relationships due to resource constraints of bidders can be hard to recognize from the outside and even more difficult to quantify. However, for the use of CAs this is not necessary as CAs enable bidders to express both complementary and substitute relationships in their bids.

Literature reviews of auctions conducted in the RE sector are provided in del Río and Kiefer (2023) and Fleck and Anatolitis (2023). Theoretical analyses of RE auctions can be found in Kreiss et al. (2017a), Haufe and Ehrhart (2018), Kitzing et al. (2019), Szabó et al. (2020), Kreiss et al. (2021), Fabra (2021), and Fabra and Montero (2022). Various design elements are discussed by del Río et al. (2015a), Gephart et al. (2017), and Anatolitis et al. (2022). Jansen et al. (2022) provide an overview of auction designs used worldwide for offshore wind. General design issues of wind right auctions with particular reference to the US are discussed in Ausubel and Cramton (2011).

The majority of RE auctions employs sealed-bid formats (95% in Europe and 91% worldwide) with PaB pricing (84% in Europe and 91% worldwide) (del Río and Kiefer, 2021; Mora et al., 2017; AURES II, 2022).

A distinction is made between *reverse auctions* and *forward auctions* based on the direction of the payment flow between the bidders and the auctioneer. Reverse RE auctions allocate

[2] The bid prices were \$59.9 per MWh for 100 MW, \$58.4 for 200 MW and \$54 for 1000 MW (IRENA and CEM, 2015).

support to bidders who submit the lowest bids. These are mostly energy-related payments,[3] but capex support has also been provided. In forward auctions, the bidders with the highest bids win and have to make corresponding payments to the auctioneer. By now, forward auctions have become prevalent for the allocation of offshore wind rights.

Most RE auctions are multi-item auctions, where support for multiple projects or multiple rights to build and operate RE plants are allocated (del Río and Kiefer, 2021). In many onshore auctions (AURES II, 2022) and several offshore auctions (e.g., RVO, 2016a; Crown Estate, 2021a; BNetzA, 2023a), developers had the opportunity to submit multiple bids for different projects. This argues for the use of CAs, where developers can properly consider the complementary and substitute relationships between their projects.

This chapter discusses the suitability of CAs for RE. In particular, CAs are well suited to exploit synergy potentials and thereby increase efficiency, and they can also capture substitute relationships between projects. Section 4.2 briefly introduces CAs; Section 4.3 discusses auction-relevant specifications of the RE environment; Section 4.4 presents advantages and challenges of CAs for RE; Section 4.5 summarizes and derives policy implications.

4.2 Combinatorial auctions (CAs)

CAs can be used for both selling (forward auctions) and buying (reverse auctions). This section provides an introductory example of CAs, introduces two combinatorial auction formats, and summarizes the applications of CAs in the practice.

4.2.1 Introductory example

To illustrate the functioning and benefits of CAs, we begin with a simple and stylized example. Two offshore wind farms are to be developed at respective sites A and B, which are auctioned off in a forward auction. Three developers, bidders 1, 2, and 3, are interested in building wind farms at these sites. Table 4.1 states their valuations for the single sites and the combination of the sites.[4] For bidders 1 and 2, sites A and B are perfect substitutes, i.e., they are interested in only one of the two sites, which may be due to budget constraints. Bidder 3 has synergies

[3] Most of the support is an ongoing subsidy that is directly tied to the amount of energy supplied to the grid and is typically paid per unit of energy (Gephart et al., 2017). Typical forms of ongoing support include a fixed price per MWh (also called the FIT), a one-sided FIP, and a CfD, or a guaranteed minimum price (Anatolitis et al., 2022). Developers participating in FIP and CfD are obligated to sell electricity on the market and receive an extra support payment. The premium is the difference between the awarded price and the electricity market revenue. If the electricity market revenues fall below the awarded price, the premium for FIP and CfD is the same. However, when the market revenues exceed the awarded price, FIP allows generators to keep the surplus revenue, while under CfD, the additional revenue must be transferred back to the government.

[4] The valuations approximate the dollar amount resulting from actual offshore wind auctions. The 2018 and 2022 US auctions sold three and five 900 MW sites, respectively, for \$135 million and \$130 to \$174 million each (BOEM, 2018; BOEM, 2022). In the 2021 UK auction, four 1,500 MW sites were sold for between £114 and £231 million (Crown Estate, 2021b).

from developing both farms, leading to a higher willing to pay for both sites than the sum of the single sites valuations.[5] In the efficient allocation, Bidder 3 receives both sites because it assigns the highest (total) value to them.

Table 4.1: Example of three bidders and their valuations (in million €) for two offshore wind sites, A and B, that are auctioned off in a forward auction.

	A	B	A & B
Bidder 1	135	135	135
Bidder 2	155	155	155
Bidder 3	130	130	300

When sites are auctioned in separate auctions, bidders can consider synergies only based on assumptions about competitors' valuations and bids, or after one site has been allocated. If sites A and B are auctioned sequentially, the efficient allocation requires that Bidder 3 – with the lowest valuation for site A – wins the first auction. If Bidder 3 outbids Bidders 1 and 2 in the first auction at a price above 155, with the expectation of winning both items at a total price below 300, Bidder 3 runs the risk of making a loss because it cannot outbid Bidder 2 on both sites below 300. Either Bidder 3 wins only one site at a price above 155 or both sites for more than 310. This is called the *exposure problem* (e.g., Milgrom, 2004; Meng and Gunay, 2017). The risk of exposure also exists if the two sites are auctioned simultaneously in a non-CA. As a result, the allocation may be inefficient, i.e., Bidder 3 may win only one site at a loss, or Bidder 3 may bid cautiously so that bidders 1 and 2 win. For a further comparison of sequential and simultaneous auctions with CAs, see Section 4.4.1.

In a CA, bidders can express their valuations for single sites and site combinations without risk, and the auction's allocation rule takes into account the expressed synergies and substitute relationships. This is achieved by allowing bidders to submit not only single bids on single sites, but also package bids for combinations of multiple sites, and by making these bids exclusive (XOR) so that at most one bid (either a single bid or a package bid) from each bidder can win. Thus, for each bid, the bidder can optimize conditional on that bid winning. This avoids the exposure problem and can improve the efficiency of the auction outcome, especially when items are complementary.

Assume that the bidders bid their valuations in Table 4.1, which is a dominant strategy in the generalized Vickrey auction (GVA) (see Section 4.2.2). To determine the winners, the auctioneer maximizes the sum of bid prices while ensuring that at most one bid from each bidder wins (see Section 4.2.2). Thus, Bidder 3 wins with the package bid of 300. Obviously,

[5]Bidder 1 and 2 value a site and also both sites at 135 and 155 (million €), respectively. Bidder 3 has synergies from developing both farms. Bidder 3 is willing to pay 130 for one site but 300 for both sites, which is more than the sum of the bidder's values of the two single sites.

if the bid prices are equal to the bidders' valuations, this allocation rule allocates efficiently.[6]

4.2.2 Combinatorial auction formats

In CAs, bidders can submit bids for single items and package bids for combinations of items. This section the GVA and the combinatorial PaB auction.[7] These CAs share the *allocation rule* that the winning bids maximize (minimize) the sum of bid prices in a forward (reverse) auction, subject to the conditions that each item is allocated only once and no more than one bid from each bidder can win.

The generalized Vickrey auction (GVA)

Assuming private values,[8] bidders in the GVA have a weakly dominant strategy to bid their valuations.[9] Dominance of a bidding strategy means that it is optimal for bidders to bid their private values independently of competitors' bids. This eliminates the need for a bidder to spend time and money investigating competitors' valuations, making assumptions about their bidding strategies, and determining an advanced bidding strategy.

The GVA *pricing rule* sets the price a bidder has to pay (receives) equal to the lowest (highest) bid price with which the bidder would have won its item or package given the competitors' bids in a forward (reverse) auction (Krishna, 2010; Milgrom, 2004). Thus, the price to be paid (received) is weakly lower (higher) than the bidder's bid price, i.e., the payment is lower (higher) than or equal to the bid price. If the bidders in the example in Section 4.2.1 follow the dominant strategy, Bidder 3 wins sites A and B and must pay 290, because it must bid at least 290 for the package of A and B to outbid the competitors' highest feasible bid-price combination, which is 135 for A and 155 for B (or vice versa).

The *dominant strategy* and the resulting *efficient allocation* are the main advantages of the GVA. However, it also has weaknesses (e.g., Ausubel and Milgrom, 2006; Rothkopf et al.,

[6]The alternate allocations achieve sums of bids of 290 (Bidder 1 receives A or B and Bidder 2 receives B or A), 265 (Bidder 1 receives A or B and Bidder 3 receives B or A), 285 (Bidder 2 receives A or B and Bidder 3 receives B or A), 135 (Bidder 1 receives A & B), or 155 (Bidder 2 receives A & B).

[7]We consider these two auction formats, because the GVA is known for its theoretical virtues, while PaB is the most common pricing rule in practical applications of CAs (Palacios-Huerta et al., 2024) and in non-CAs for RE (see Section 4.2.2). Other sealed-bid CAs are UP auctions and core-selecting auctions, also referred to as modified GVA (Pekeč and Rothkopf, 2003; Day and Raghavan, 2007; Day and Milgrom, 2008). Examples of dynamic (i.e., multi-round) CAs are considered by Ausubel et al. (2006), Ausubel and Cramton (2011), and Ausubel and Baranov (2017).

[8]Private values refer to individual valuations of auction items (e.g., sites), where the valuations are known exclusively to the bidders themselves (i.e., private information) and may vary among bidders (e.g., Haufe and Ehrhart, 2018, for a RE setting). This is assumed in the example in Section 4.2.1.

[9]This is because the GVA is a VCG mechanism (Vickrey, 1961; Clarke, 1971; Groves, 1973). VCG mechanisms induce agents to reveal their preferences under weak assumptions, and are the only mechanisms with the properties of providing a weakly dominant strategy and resulting in an efficient allocation (Green and Laffont, 1979; Holmstrom, 1979). For textbook coverage with respect to auctions, see Krishna (2010) and Milgrom (2004).

1990, and Appendix C.1): instances of low (high) prices in forward (reverse) auctions, non-monotonicity of revenue, different prices for homogeneous items, possibility of cooperation to win at low (high) prices by bidding high (low), profitability through participation with multiple identities, no dominant strategy with budget restrictions. We illustrate these drawbacks in Appendix C.1. Furthermore, if bidders are concerned that the extensive information they reveal is abused, they may be reluctant to reveal their valuations. In addition, the rather complex calculation of prices (payments) complicates the understanding of the GVA, which could lead to an acceptance problem.

The combinatorial pay-as-bid auction (PaB auction)

In a forward (reverse) PaB auction, the pricing rule is straightforward: Each bidder pays (receives) the price of its winning bid. Consequently, bidders typically bid less (more) than their valuations (costs). For instance, Bidder 3 in Table 4.1 will bid less than 300 for the package of A and B in a combinatorial PaB auction, where the precise amount depends on the bidder's beliefs about competitors' bids. This introduces strategic complexity for bidders and efficiency cannot be guaranteed. Nevertheless, Palacios-Huerta et al. (2024) find that combinatorial PaB auctions are common in applications, particularly in public sourcing. One reason is the provision of price certainty for bidders, who know their price in case of winning when submitting their bids. PaB also circumvents some issues of the GVA (e.g., Ausubel and Baranov, 2017): adding bidders or increasing bids can only increase the auctioneer's revenue and reserve prices (lower or upper bounds on prices) can be straightforwardly implemented by lower (upper) bounds on bid prices. Moreover, the acceptance problem is mitigated.

In the RE context, the PaB design offers a means to address the weighting issue discussed in Section 4.3.2. The PaB auction is also an obvious candidate for RE applications because its non-combinatorial cousin is currently the most common auction format in the RE sector (Szabó et al., 2020; AURES II, 2022).

4.2.3 Applications of CAs

CAs are widely used in various public sectors, including the electricity sector (see Table 4.2). However, for the RE sector, they are rarely used and discussed in the literature, probably because this field is still relatively young and developing.[10] To the best of our knowledge, the only instance of a CA being carried out for RE is the Borssele I and II auction (see Section 4.4.3). In addition, the design of an upcoming auction in Germany to award sites for wind farm electrolyzer projects (SoEnergieV, 2022) is currently being revised to a CA format.

[10] In the private sector, CAs are mainly used for industrial procurement (reverse auctions). Bichler et al. (2020) propose CAs for RE support in the context of regional targets. For onshore wind, they emphasize the potential benefits of CAs where efficiency gains can arise not only from economies of scale from the bidders' perspective but also from system-oriented regional dispersion.

Table 4.2: Applications of combinatorial auctions in the public sector. Data from Palacios-Huerta et al., 2024; Herrero et al., 2020; MARI, 2023; RVO, 2016a.

Combinatorial auctions in non-energy sectors

Sector	Direction of payment flow	Payment rule[1]	Countries
Sourcing of bus services	Reverse	PaB	Finland, Sweden, UK
Sourcing of school meal services	Reverse	PaB	Chile
Sourcing of miscellaneous government services	Reverse	PaB	Denmark, Ireland, Sweden
Sale of government plant	Forward	PaB	US
Rental of floor space	Forward	PaB	Netherlands
Telecommunications	Forward	PaB[2], GVA[2]	Australia, Austria, Canada, Denmark, France, Ireland, Israel, Mexico, Montenegro, Netherlands, New Zealand, Nigeria, Norway, Portugal, Romania, Slovakia, Slovenia, Switzerland, Trinidad, UK, US

Combinatorial auctions in the energy sector

Sector	Direction of payment flow	Payment rule	Countries
Sale of electricity generation capacity	Forward	PaB[3]	Belgium, Denmark, France, Germany, Netherlands, Portugal, Spain, US
Day-ahead electricity markets	Forward & Reverse	UP	European countries
Balancing energy markets	Reverse	UP	European countries (Manually Activated Reserves Initiative (MARI) platform, currently operational: Austria, Czechia, Germany)
Sourcing of electricity generation capacity	Reverse	PaB	Chile
Renewable Energy	Reverse	PaB	Netherlands

1: GVA: The generalized Vickrey auction, including core-selecting as modified GVA; PaB: Pay-as-bid, including multi-round auctions in which bidders pay their bid; UP: Uniform pricing. 2: Some are multi-round CAs. 3: All are multi-round CAs.

4.3 Auction-relevant specifications of the RE environment

Crucial to the design of well-functioning auctions are the specifications of the particular application. For RE auctions, important aspects are the extent of synergies between projects, the comparability of projects in terms of capacity or energy, and the possibility of realizing non-awarded projects. To structure the discussion, it is useful to distinguish between auctions of specific sites and auctions where developers compete with their individual projects at different sites.

4.3.1 Auctions of specific sites

Auctions of specific sites allocate rights to build and operate RE plants at those sites, potentially in combination with support, or just support for projects that have already been approved, which is typical for offshore wind. Table 4.3 illustrates the classification with examples.

Table 4.3: Auctions for offshore wind sites: classification and examples

Auction item	Payment flow	Examples
Wind right	Forward	2018 US Atlantic Wind Lease Sale 4-A (BOEM, 2018) 2020 UK Offshore Wind Leasing Round 4 (Crown Estate, 2021a) 2022 US Pacific Wind Lease Sale 1 (BOEM, 2022) German tenders for offshore wind sites since 2023 (WindSeeG, 2023, §16 et seqq. and §50 et seqq.)
Wind right & support	Reverse	2016 Dutch Borssele Wind farm sites I and II (see Section 4.4.3) The first German offshore wind auctions: tenders for existing projects and tenders for centrally pre-investigated sites (WindSeeG, 2021, §26 et seqq. and §23 et seqq.) German offshore electrolyzer projects* (SoEnergieV, 2022)
Support	Reverse	UK & US separate auctions of CfDs after the auctions of wind rights (e.g., GOV.UK, 2022; Dogger Bank, 2022)

* A reverse auction will also be used to allocate capex subsidies for offshore electrolyzer projects in Germany (SoEnergieV, 2022), where the winning bidders also acquire the right to build and operate the entire plant.

The auctioning of specific sites exhibits characteristics that argue for the use of CAs. To illustrate this point, we consider the example of auctioning wind rights. First, in the examples in Table 4.3, multiple sites are often tendered together, especially if they are adjacent. Second, the auctioneer usually determines or knows the relevant parameters of the installation. Offshore sites are often pre-investigated by government agencies (WindSeeG, 2023, §50 et seqq.). The capacity is more or less fixed and energy production can be estimated fairly accurately, leaving limited leeway for developers.[11] Third, there is exactly one chance for the bidders to win the auction and thus build and operate the farm(s). This is an important difference from the setup in Section 4.3.2. Fourth, offshore wind farms generally require large investments.[12]

In summary, certain sites for certain farms are usually auctioned together, there may be significant synergies between sites and some bidders may not be interested in acquiring all sites due to budget constraints. As shown, CAs are particularly attractive under these conditions and have advantages over other forms of auctions. The design of a CA is straightforward because the situation closely matches the setup of the basic model from Section 4.2 (cf. Ausubel and Cramton, 2011).

The situation is different for auctions that allocate support to projects that have already been approved. Since developers have already acquired the wind rights, the synergies have already been captured, so that a CA does not open up any further potential.

4.3.2 Auction-determined set of individual projects

Auctions that select among a number of individual projects are typical for allocating support for onshore technologies (e.g., Gephart et al., 2017). In these auctions, a predetermined quantity, e.g., capacity, is tendered for a specific technology or several technologies together.[13] Developers participate with one or more individual projects and submit a bid for each project, indicating the capacity and support, e.g., a payment per unit of energy fed into the grid (e.g., del Río et al., 2015a). Thus, developers compete with their individual projects for the awards. The developers with the lowest support bids win, which obliges them to realize the project with the capacity specified in the bid in order to receive the support. In this format, the total

[11]It is common to grant the developers slight changes and thus flexibility in the realization of the wind farms within a certain limit in order to give them the opportunity to implement technical innovations and new standards (Anatolitis et al., 2022). Examples include the German Renewable Energy Sources Act (WindSeeG, 2023) and the Dogger Bank Wind Farm (Dogger Bank, 2021). In the latter case, the installed power of the planned turbines was upgraded after the auction of CfDs, but the number of turbines was reduced, so that the total installed power of the wind farms remained almost unchanged (Dogger Bank, 2021). The maximum size (MW) of the converter also limits flexibility. Note that the sites were identified by the consortium and permitted by the UK government without being auctioned off in an auction of wind rights (Dogger Bank, 2022). Anatolitis et al. (2022) analyze the AURES II Auction Database, including data on auction design and outcomes from EU member states and the UK, and find no convincing evidence that flexibility for bidders has a significant impact on auction prices.

[12]The investment costs of a 1 GW offshore wind farm are estimated at € 3 to 4 billion (e.g., Rubio-Domingo and Linares, 2021).

[13]Besides capacity as the tender quantity, energy and budget are also in use (Gephart et al., 2017).

capacity of the awarded projects is determined in advance, but the projects that make up the total quantity are not known in advance.

When using a CA, the auctioneer must compare the sizes of the projects in a single dimension, such as capacity or energy production. While this task is relatively straightforward in the settings of Section 4.3.1, it becomes more complex in this context (Section 4.3.2) because the developers' projects are not tied to a specific site and may differ not only in their capacity but also in the energy production per unit of capacity. This challenge applies not only to the increasingly common multi-technology auctions, in which, for example, wind and solar projects compete, but also to technology-specific auctions, e.g., due to different locations. These differences require the auctioneer to weight the bids of the projects according to some criterion, such as expected energy production. However, this approach may create undesirable bidding incentives if the bidders weight their projects differently than the auctioneer (see Section 4.4.2).

In addition, the different bid dimensions capacity and energy complicate the application of the GVA, because the payment to a successful bidder is determined by comparing alternative allocations. The bids in these allocations may relate to a different capacity and energy amount, which complicates the comparison that relies on accurate comparability (Leyton-Brown et al., 2017). A CA with PaB pricing circumvents this problem.

Another difference from Section 4.3.1 that reduces the potential of CAs is that a bidder who was unsuccessful with a project in one auction can participate again with that project in a future auction or even realize the project without support. Therefore, synergies between projects are not necessarily lost if a bidder wins only part of a package, in particular synergies due to administrative and maintenance costs.

In summary, CAs for individual projects in the environment common for onshore technologies are less likely to capture synergies and present more challenges (see Section 4.4.2) than CAs for specific sites.

4.4 Relevant aspects of designing CAs for RE

This section considers the advantages of CAs over non-CAs, the challenges of CAs, and an application.

4.4.1 Advantages of CAs over non-CAs

We compare CAs in terms of complementary or substitute project relationships with the common auction procedures for RE, where, e.g., support or wind rights are auctioned sequentially or simultaneously (e.g., AURES II, 2022). The comparison is summarized in Table 4.4.

If the items are auctioned sequentially, there are two cases. First, several auctions are conducted independently, one after the other, usually months or even years apart. This applies to both auctions of wind rights and the support for onshore technologies (see Sections 4.3.1 and 4.3.2). If developers already have existing plants nearby, they can benefit from synergies that result in reduced administration and maintenance costs. One example is Germany's 2017 offshore wind auction (WindSeeG, 2023, §26 et seqq.), where EnBW submitted a zero-cent bid, citing synergies from sharing infrastructure with two existing wind farms nearby (Clean Energy Wire, 2017). However, if the construction dates of the wind farms are different due to the time gap between the auctions, potential synergies from volume discounts and lower construction costs can hardly be exploited. The second case is one auction, in which several items (e.g., wind rights) are auctioned off consecutively within hours or days. The interesting scenario is when bidders can win more than one item. For example, in the 2021 UK offshore wind auction, two bidders each won two neighboring sites (Crown Estate, 2021b), which indicates synergies. Once a site has been won, the bidder can take synergies into account in the bids for additional sites without risk.[14] The challenge is the bid for the first site: If it incorporates synergies, the bidder risks being exposed to potential losses; if it does not incorporate synergies, the bidder reduces the chances of winning. In both cases, bids in sequential auctions can only partially include substitute relationships between projects, but hardly those between packages of projects.

When items are auctioned simultaneously, bidders submit their bids without knowing the opponents' bids. For developers interested in only one of the sites, permitting exclusive bids for single sites in a simultaneous non-CA would facilitate bidding (e.g., Sandholm, 2002; Nisan, 2006). Exclusive bids have been implemented in non-CA RE auctions, e.g., the 2014 Dubai solar auction (IRENA and CEM, 2015) and the 2017/18 offshore wind auctions in Germany (WindSeeG, 2021, §26). For developers who are interested in more than one site, the exposure risk would still exist.

An example is the 2023 offshore wind auction in Germany, where three sites in the North Sea, A, B and C, were auctioned simultaneously in a price-only forward non-CA (BNetzA, 2023a; BNetzA, 2023b; WindSeeG, 2023, §16 et seq.). Each site is for a 2 GW wind farm. A bidder may win up to all three sites. It is likely that there were bidders who wanted to win only two or even one site due to budget constraints. These bidders face a difficult decision problem. When a bidder interested in only one site submits bids for two or three sites to increase the probability of winning, it takes the risk of winning multiple sites. If, on the other hand, the developer decides to bid on only one site, the question becomes which site to choose. The level of competition can then vary significantly among different sites, depending on the bidding decisions made.

[14] Betz et al. (2017) show in an experimental study that sequential auctions can be quite effective in capturing efficiency gains of interdependent items.

In a CA, the issue above is resolved through the exclusivity of the bids. Developers who can execute only two projects but not all three submit package bids for A & B, A & C, and B & C.[15] The same bidding logic applies to developers who can execute only one project.

Table 4.4: Comparison of CAs with non-CAs in terms of complementary or substitute project relationships

	CAs	Sequential auctions		Simultaneous auctions
		Apart	Consecutive	
Complementary projects (synergies)	++	$+^1/\bigcirc^2$	$\bigcirc^2$	$\bigcirc^2$
Substitute projects	++	+	+	–
Substitute packages of projects	++	◯	◯	$-^2$

++ very good, + good, ◯ fair, – poor;
1: The first project(s) already exist(s); 2: Exposure risk

4.4.2 Challenges of CAs for RE

This section presents challenges of CAs by analyzing the effects of selected design elements on bidding incentives, efficiency, and project realization. Because the discussion is more relevant to the setting in Section 4.3.2, we focus on reverse support auctions. The results presented are derived from the analysis in Appendix C.2.

The general rules of the CA provide that a package bid contains only one bid price (see Section 4.2), which is referred to as the *package bid price* format. In the practical application of CAs, a bid price must often be submitted for each component (e.g., project) of a package bid (e.g., Section 4.4.3), which is referred to as the *component bid price* format. One advantage of the component bid price format is the precise assignment of bid prices and, thus, support to projects. However, determining the winning bid combination requires a single price for each package bid. Therefore, the auctioneer must calculate the package bid price as a weighted average of the component bid prices. Weighting is not a problem in auctions where the auctioneer knows the projects and their size well (cf. Section 4.3.1). However, if bidders participate with their individual projects, the auctioneer often lacks information about the projects or weighting them accurately is too costly.

[15] If the award of a site comes with a commitment to build the wind farm, which is usually the case, a potential package bid for all three sites should be waived.

Distorting bidding incentives

In this analysis, we assume that the developers will realize the awarded projects. When the package bid price format is used, bidders in the GVA have an incentive to submit truthful bids (see Section 4.2.2), i.e., the weighted average (annualized) costs of their projects, and to submit the weighted average costs with mark-ups in the PaB auction. Thus, the CA does not create distorting bidding incentives. The outcome can be inefficient if the developer's calculation and the auctioneer's bid evaluation do not match, i.e., if they evaluate the energy output of the projects differently.

In the component bid price format, weighting is more critical. There are no distorting incentives if the auctioneer and the developer use the same weights. If not, the developer has an incentive to spread the component bid prices as widely as possible, regardless of project costs, while still achieving the desired probability of winning. The bid price of projects that the auctioneer overweights (underweights) relative to the developer is increased (decreased). An inefficient outcome is then very likely.

The auction design should create incentives for bidders to align their bids with actual project costs, which simplifies bidding and provides valuable information to the auctioneer. Incentives to spread component bid prices not only counteract this, but are also associated with a higher non-realization risk (see the next section).

Non-realization risk

Non-realization risk arises when developers submit bids for projects, not all of which they will realize if their bid wins. This risk exists for both auction formats, even if auctioneer and developers weight the projects equally.

In the package bid price format, it is optimal for the developer to submit the actual weighted average costs of the projects in the GVA (see Appendix C.2.3). Thus, if the projects' costs are different from each other, the payment to the package bid may be less than the highest project cost. The developer may then have an incentive (depending on the penalty) not to realize the expensive project(s). The non-realization risk also exists in a PaB auction.

In the component bid price format, the non-realization risk exists even if the costs of the projects in the package are equal and the auctioneer and developers weight the projects equally. Bidders have an incentive to spread the bid prices and thereby maintain the winning probability (see Appendix C.2.3). Only the projects with high bid prices will be realized, but not those that receive little support. There is even an incentive for developers to extend a bid by including a project with a low bid price, with no intention to realize this project.[16]

[16]Such behavior of including dummy projects could be observed in the 2016 PV pilot auction in Greece (Papachristou et al., 2017). One developer participated in the auction with additional projects that it did not intend to realize, in order to meet the auctioneer's competition requirement for holding the auction.

4.4.3 An application of a CA: The auction of Borssele I and II

An example of a CA for RE is the reverse auction of the two offshore wind farm sites Borssele I and II (RVO, 2016a). The rules allow a bidder to bid for each site and for the package of the two sites. Thus, the auction enables bidders to translate their synergies into bids. Component bid prices apply, i.e., package bids must include individual bid prices for each site. A package bid will only win if its component bid price for each site is (weakly) lower than all single bids for this site. This rule does not correspond to the idea of a CA, which aims to minimize the total costs and not the prices of the individual components. When package bids compete, the bid with the lower average component bid price wins.

Of the 28 bidders, 21 were subsidiaries of DONG Energy (RVO, 2016b), each of which submitted only one package bid, and one of them won the auction. Presumably, DONG's multiple participation was driven by the restriction under which a package bid could win, and the subsidiaries' bids contained different component bid prices with similar means. This strategy increases the probability of outbidding different combinations of competing single-site bids.[17]

To assess this auction and its outcome from a policy perspective: Considering the administrative and legal costs for founding the subsidiaries, DONG's sophisticated behavior was certainly costly, but it suggests that there are high synergies between neighboring offshore wind farms. Since DONG also won with a package bid, the CA was effective in capturing synergies, thus contributing to efficiency. However, an auction design that incentivizes such behavior raises the aforementioned additional costs. A simple change of the design to a CA that allows bidders to submit multiple package bids, of which only one can win, would have avoided these costs while allowing for the same bids and outcome.

4.5 Conclusion and policy implications

For developers of RE projects, it can be assumed that in many cases there are synergies between their planned projects. In addition, substitute relationships between projects or project bundles may exist, e.g., because the number of projects that a developer can realize is limited due to budget or other resource constraints. CAs are a class of auction formats that facilitate the consideration of both synergies and substitutes.

From a bidder's perspective, CAs eliminate the risk of obtaining a subset of projects that are valuable only as part of a larger package. Furthermore, exclusive bids enable developers to bid on alternative packages without risk of winning more projects than they can afford. Eliminating these risks incentivizes more "ambitious" bids, i.e., higher bids in forward auctions

[17] The fact that different auction designs can create differing bidding incentives is pointed out by Haufe and Ehrhart (2018) in the context of RE auctions and by Ausubel et al. (2014) in a more general context.

and lower bids in reverse auctions. From the auctioneer's or society's point of view, this results in an allocation that maximizes the total value and lowers the cost of the transition to CO_2-neutral power generation.

A drawback of CAs is the additional complexity compared to non-CAs. However, participating with multiple projects in any auction requires evaluating multiple possible outcomes, taking into account complementary or substitute relationships. Bidding in a CA is simple in the sense that business cases can be straightforwardly translated into bids. Moreover, bidders do not have to bid on all projects or combinations of projects, but only on those they are interested in. Therefore, we do not consider the increased complexity of a CA to be a significant disadvantage for bidders. Rather, if a bidder's planned projects include complements or substitutes, the benefits of a CA are likely to outweigh the complexity of the procedure. This also applies to a certain extent to extended non-CA formats that allow exclusive bids on single projects. Such an extension can provide a simple format to help developers express substitute relationships. However, it falls short when it comes to capturing synergies and is not as comprehensive and effective as a CA.

Designing and implementing a CA is straightforward if multiple rights to build and operate RE plants at specific sites are to be allocated with or without support. Here, the technology is usually predetermined and there is little room for capacity variation, so the energy yield can be estimated fairly accurately in advance. This applies, for example, to auctions of offshore wind rights. Even if energy or capex support is paid later, the total payment to a winning bidder is simply the product of the auction price and the energy or the capacity. Since the energy or the capacity is (approximately) the same for all bidders, it is not a strategic variable. This makes it easy to compare bid prices.

In other settings like the support of onshore technologies, requirements such as component bid prices within package bids may arise.[18] Component bid prices, however, may create distorted incentives. These include widely spread component bid prices that are not based on project costs, or the strategic non-realization of awarded projects.

We therefore recommend to use package bid prices as a general rule. Component bid prices should only be considered if the costs of the individual projects differ significantly. If component bid prices are used, they should be accompanied by appropriate measures to mitigate strategic distortions.

Our results also shed light on the use of CAs for different support mechanisms. In the case of fixed support payments (e.g., capex support), their application is straightforward. The same applies to forward auctions, where winning bidders have to make fixed payments instead of receiving support. It also applies to energy-related support (see Footnote 3) if the

[18]This is because in such auctions, projects are not pre-specified by the auctioneer, but are proposals made by the bidders. Onshore projects typically vary in size, location, cost, and possibly even technology (see Section 4.3.2).

auctioneer is able to estimate the amount of energy fairly accurately. If this is not the case, CAs may need to employ the aforementioned measures to prevent strategic distortions.

The non-realization risk can be effectively addressed by low maximum bid prices in reverse auctions (or high minimum bid prices in forward auctions) or penalties. Penalties should be set as high as possible, without constituting a barrier to participation. Kreiss et al. (2017a) recommend the use of financial prequalifications (e.g., bid bonds) because the sunk-cost nature of physical prequalifications tends to counteract participation. The non-realization risk can also be mitigated by the rule that a bidder may only submit a package bid if it also submits single bids for all projects in the package. The package bid specifies an alternative price that will be applied if the package bid wins, which eliminates the incentive to include "virtual" projects that the bidder never intends to realize. It also reduces the incentive to spread component bid prices, as the bidder runs the risk that only the low-priced projects will be awarded.

When designing a CA for RE, formats in which bidders pay their bid, such as the PaB auction, may have advantages because they avoid some problems with calculating prices that may arise in auctions with second-pricing rules, such as the GVA. Another point in favor of a PaB rule is its potential for greater acceptance than the GVA pricing rule.

Our analysis also allows us to assess the integration of CAs into the RE policy landscape and their acceptance and feasibility. For auctioning projects at specific sites (Section 4.3.1), this can be rated as very good because of the advantages of CAs and their straightforward implementation. If auctions are to be used for the selection of different individual projects (Section 4.3.2), a more differentiated and context-dependent assessment is required.

In addition to the auction price, other goals must be considered when expanding RE through auctions, such as energy system reliability, security of supply, technological diversity, or a less intermittent electricity supply (e.g., del Río et al., 2015b; Peter and Wagner, 2021) in the context of overall efficiency. Some of these goals might be incorporated into an auction, which leads to multi-attribute auctions. These can be designed as CAs or non-CAs to best achieve a combination of objectives by weighting and aggregating the objectives in a value function (e.g., Che, 1993) or through discriminatory instruments (e.g., Kreiss et al., 2021).[19] In a multi-attribute context, CAs retain their advantages over non-CAs. For example, if continuity of electricity supply is an additional criterion in the auction, project combinations that contribute to this criterion become more valuable.

Overall, CAs are an attractive tool when interrelated projects are up for bidding in the same RE auction event. This applies in particular when rights to build and operate RE

[19]Examples of multi-attribute auctions in the RE sector in Germany are the offshore wind auction for centrally pre-investigated sites (WindSeeG, 2023, §50 et seqq.), which also takes into account ecological aspects, the onshore wind auctions with the reference yield model to compensate for locational disadvantages (EEG, 2023, § 36h), and the auction of sites for wind farm electrolyzer projects (SoEnergieV, 2022), which also takes into account the amount of hydrogen produced.

plants at specific sites are auctioned, possibly in combination with support. CAs have weaker advantages when there are synergies between projects that can be awarded in auctions at different times, as is often the case in auctions for onshore technologies. Like any auction, a CA must be tailored to fit the specific application.

Chapter 5

Conclusions and Outlook

The transition to climate neutrality requires a rapid and reliable expansion of RE, and auctions have become a central policy instrument to allocate development rights of RE projects and support or hedging instruments. Designing auctions that meet policy objectives while taking into account different types of uncertainty in RE projects is challenging. Well-intended design elements can sometimes be difficult to implement or may even create undesirable incentives. Against this background, this thesis provides theory-driven guidance for policy makers on how to design auctions for RE expansion and how specific auction-design choices affect incentives and expected outcomes.

5.1 Summary and policy implications

This thesis investigates three auction-design questions in the RE context that have not been studied theoretically in the existing literature: the comparison of mandatory versus voluntary pre-auction investment in information acquisition (Chapter 2); the comparison of CfDs and payment auctions with respect to project realization probability (Chapter 3); and the potentials and challenges of CA applications for RE and relevant aspects of designing CAs (Chapter 4).

Chapter 2 studies two settings of investment in information acquisition to mitigate cost uncertainty. In the mandatory setting, participants are required to invest in information acquisition prior to entering the auction; in contrast, the voluntary setting allows participants to decide whether to invest before the auction or to participate without prior investment, accepting uncertainty and investing after winning the auction. By analyzing the voluntary setting and providing a comprehensive analytical comparison with the mandatory setting, this chapter contributes to a deeper understanding of auction design under cost uncertainty. Our theoretical model identifies five types of symmetric equilibria and compares the settings in terms of participation, efficiency (expected welfare), and expected profits. The results indicate that the voluntary setting yields weakly higher expected participation and weakly higher expected welfare. It also leads to weakly higher expected profits of participants under realistic conditions. While the auctioneer's expected profit can favor either setting depending on different parameters, the voluntary setting shows an advantage for the auctioneer when information costs are high. By providing theoretical insights into the comparisons, this study contributes to the broader discussion on auction design and procurement policy. In practice, if investment in information acquisition as a central part of project preparation incurs sunk cost that could exclude potential bidders from participation, the auctioneer should allow bidders the option to postpone investment. In expectation, the voluntary feature improves participation, welfare, bidders profits, and possibly the profit of the auctioneer.

Chapter 3 contributes to the current policy debate on CfDs by providing a theoretical foundation. Among support and hedging instruments, CfDs have become the default in many countries and are promoted by the European Commission. On the other hand, payment auctions – where the electricity sales are unregulated but winners must pay for the right to build energy plants – have also become established. Focusing on the non-realization risk and the induced welfare losses, we compare two-sided CfDs with payment auctions. Contrary to the conventional wisdom, our analysis shows that if developers can realized the without government support, the non-realization risk is higher in CfD auctions than in payment auctions for risk-neutral participants with different financing costs. Risk aversion further amplifies this effect. Thus, neither risk aversion nor lower financing costs justify preferring CfDs. CfDs are particularly useful to support RE expansion when developers cannot realize projects solely with expected electricity market revenues and require government support, but no lump sum subsidy from the auctioneer to the developers is available. Given asymmetric information – developers know the economic conditions of their projects best – the auctioneer should leave the choice between a CfD auction and a payment auction to the market. Therefore, we propose a mechanism in which developers decide competitively between these two auctions. If at least one developer can realize the project without a CfD, the payment auction takes place, which results in a payment from the developer to the auctioneer. This mechanism is efficient, and selects the auction format with the higher realization probability in most cases. This design prioritizes payment auctions, while securing government-backed support through CfDs when required for offshore wind expansion. Therefore, the proposed mechanism increases participation, raises the realization probability, and reduces unnecessary barriers to market-based development of RE. A further insight is that in payment auctions, requiring part of the winner's payment to the auctioneer upfront (before the implementation decision) as sunk cost increases realization probability. Once sunk, the incurred payment no longer affects the implementation decision, and a smaller remaining payment makes project realization more attractive. Prepayment may lower the net present value of the payment and thus lower auction revenue due to higher financing costs. However, ensuring project realization and timely RE expansion is a more important policy objective than maximizing auction revenue, since delays in deployment can entail substantial welfare losses.

Chapter 4 discusses the application of CAs, which allow bidders to bid not only on individual items but also on packages of items. While CAs have rarely been used for competitive allocation of RE support, they are widely applied in other sectors because they can capture complementary and substitutive relationships between items. Complementary relationships, arising from synergy potential, and substitute relationships, due to capacity or budget constraints, are prevalent among RE projects. CAs enable developers to bid according to their own calculations and offer efficiency potential for RE expansion. We point out how this potential depends on the area of application within the RE context, and discuss implications of the design of CA. When multiple rights to build and operate RE plants at specific sites are auctioned, typically for offshore wind, the design of a CA is straightforward. Design challenges arise when the auction selects among individual projects, as is typical for onshore RE support. In such cases, even small changes to standard CAs can incentivize distorted bids, leading to inefficient outcomes or strategic non-realization of projects. Based on our theoretical analysis, we recommend using package bid prices by default, i.e., a package bid contains only one bid price. Component bid prices, i.e., submitting a bid price for each component of a package bid, should only be considered if the costs of the individual projects differ significantly and must be accompanied with measures to mitigate strategic distortions. We also recommend the PaB pricing rule for its greater acceptance and its ability to avoid some problems with calculating prices compared to GVA. Finally, the non-realization risk can be effectively addressed by low maximum bid prices in reverse auctions (or high minimum bid prices in forward auctions) and penalties.

The research questions in this thesis are motivated by practical policy discussions. The models abstract from real-world complexity while focusing on the central design question. Their main purpose is to clarify, through theoretical analysis, how auction designs shape incentives and outcomes, and to draw qualitative insights that can inform policy decision-making.

5.2 Discussions, limitations and outlook

When discussing the limitations of this thesis and avenues for future research, two central aspects are essential. First, because the research questions emerge from practical concerns, it is often challenging to generalize the models to broader theoretical frameworks. Nevertheless, we value the practical relevance of our research, as the models are deliberately designed to address policy trade-offs. Second, our models cannot fully capture the reality and are primarily qualitative. The role of theory in this context is to identify incentives and clarify effects of designs from a game- and auction-theoretical perspective, rather than to deliver precise quantitative predictions. Therefore, to maintain analytical focus on the central research questions, model assumptions are simplified. Although completeness is impossible, model extensions can incorporate relevant variations to assess their effects. Quantitative measurement and empirical validation are important subsequent steps before policy implementation but are beyond the scope of this thesis.

Future research should take these two central aspects into account: The first concerns the generalization of theoretical frameworks to broader economic theory. The second concerns applications and environmental economics extensions, with the aim of better reflecting reality and enhancing the practical relevance of the results.

Regarding the results in Chapter 2, future work could extend the analysis to forward auctions, other direct mechanisms such as first-price auctions, and multi-item auctions. Besides, alternative approaches to model information investment could allow for partial investment and thus partial information revelation, or for investment in cost improvement rather than only cost revelation. Moreover, deriving the optimal mechanism, rather than only studying the optimal reserve price in a second-price auction, would contribute more to the literature of economic theory. In addition, exploring full voluntarism in our framework, i.e., including the option to allow bidders to remain uninvested even after winning the auction, and comparing the results with similar models in existing literature would also provide further insights. In Chapter 3, the analysis is currently based on the RE-specific project timeline and the associated actual non-realization risk. These results might be generalized to other contexts, such as financial markets, where non-realization is also possible and hedging instruments play a central role. Compared to the two chapters, Chapter 4 is more practice-oriented. Nevertheless, the application of CAs can also be studied more theoretically, for instance by deriving necessary conditions for multi-criteria CAs or by analytically investigating in the implications of CAs with component bid prices.

Regarding Chapter 2, one promising extension is the investigation of centralized a priori investment in information acquisition by the auctioneer, which reflects the German auction design for centrally pre-investigated offshore wind sites. In this extension, the centralized investment in information can reduce the cost uncertainty of all potential bidders or reduce their information cost. In addition, the non-realization risk of a winning non-investor in the voluntary setting should be considered, as ex-post cost realization may exceed expectations and result in a loss. Regarding Chapter 3, a systematic analysis that differentiates various CfD forms precisely would provide useful benchmarks. As applications of CfDs and payment auctions expand, empirical studies (when sufficient data are available) and experimental studies can test the qualitative results derived from the theoretical models and provide further empirical insights. Similarly, collecting and analyzing case studies of both successful and problematic applications of CAs, as proposed in Chapter 4, will help identify when CAs are beneficial and when distorted incentives lead to undesirable results. Based on the practical examples, more detailed research questions on specific design elements and mitigation measures could be examined.

Taken together, these two research directions emphasize the importance of qualitative analysis through theoretical models and reveal the potential both for generalization to broader economic theory and for extensions that strengthen the policy relevance of environmental economics research.

5.3 Concluding remarks

When designing auctions for RE expansion, the first step is to determine a clear main objective. If multiple objectives exist, they should be consistent, non-conflicting, and ordered by priority. Once the objective is established, the next step is a careful diagnostic of the actual situation. Practical auctions, unlike textbook models, face diverse uncertainties that are crucial for their design. Measures to address these uncertainties should be explicitly considered. Based on the objective and the information structure, the auctioneer should analyze how different designs affect incentives under given circumstances and consider interactions between design elements.

There is often no "the right" design. Different choices involve trade-offs, and policy makers often must decide under uncertainty. It is the job of theoretical analysis to clarify the qualitative effects. In game-theoretical context, where outcomes depend on interactions among participants, the effect of a single design choice may be non-trivial. Combinations of design choices may have unobvious, complex effects and can change the outcomes substantially. These effects should be studied thoroughly. Good intentions do not always yield good outcomes. Good designs should avoid creating distorted strategic incentives. A design should be further analyzed beyond theoretical analysis only if such distorted incentives do not exist. This is where experimental analysis comes in to test robustness and strengthen both the internal and external validity of promising mechanisms, which are expected to have the right properties and deliver the desired results. Specific parameter choices and trade-offs should be informed by quantitative analysis and context-specific measurement.

Due to asymmetric information, policy makers should be aware of the limits of their own forecasts and should consult the sector. In fast-developing markets, such as offshore wind as observed over the last decade, accurate forecasting can be extremely difficult or even impossible. Over-regulation can pose risks such as slowing development, distorting market competition, misdirecting innovation, or even preventing value-generating trends (e.g., leveraging efficiency potential, technical progress). Calls for stronger regulatory intervention should therefore be weighed against these risks, particularly when the calls are driven by isolated controversial events or pressure from specific stakeholders.

As illustrated across the three main chapters of this thesis, it is often better to preserve market flexibility: allow the market to decide whether to invest in information acquisition before an auction; whether to realize a project with or without a subsidy or hedging instrument;

and how to price complementary and substitutive relationships into bids. At the same time, close monitoring of the outcomes in fast-developing markets remains imperative. If undesirable patterns persist, such as repeated project non-realization or the existence of dominant participants with market power, targeted regulatory measures may be justified. When intervention is necessary, it should be designed to correct market failures without creating new distorted incentives.

The three chapters in this thesis and the discussions above deliver a consistent message: Auction design matters. Poorly chosen or overly prescriptive design choices can create incentives that defeat policy objectives. Theory can and should serve as a guide to expose trade-offs and potential pitfalls. The insights developed here provide a practical map for policy makers and a foundation for further theoretical and empirical work on designing auctions for RE expansion.

Appendix A

Appendix to Chapter 2

A.1 Proof of Proposition 1 for the mandatory setting

In the mandatory setting, a firm has to invest c and will learn the private cost x_i before participating in the auction. Thus, c is a sunk cost and the participant will bid truthfully in the auction, i.e., bid x_i if $x_i < r$, and not bid if $x_i \geq r$. Given that the condidered firm participates and that there are $n, n \in [0, N]$ other participants, the expected payoff of the considered firm is:

$$\pi(x_i, n) = \begin{cases} r - x_i, \text{ if } n = 0, \\ \int_{x_i}^{r} (t - x_i) f_{(1,n)}(t)dt + (1 - F_{(1,n)}(r))(r - x_i) = \int_{x_i}^{r} (1 - F(t))^n dt, \text{ if } n \geq 1. \end{cases}$$

Let q denote the symmetric participation probability of each firm, i.e., the probability that a firm will invest c. If c is sufficiently small (e.g., $c = 0$), all firms will invest and participate (full participation), i.e., $q = 1$ and $n = N - 1$. The expected payoff of each participant is

$$\begin{aligned} \pi_i &= \int_{\underline{x}}^{r} \pi(s, N-1) f(s) ds \\ &= \int_{\underline{x}}^{r} \left[\int_{s}^{r} (t - s) f_{(1,N-1)}(t)dt + (1 - F_{(1,N-1)}(r))(r - s) \right] f(s) ds \\ &= \int_{\underline{x}}^{r} F(t)(1 - F_{(1,N-1)}(t))dt. \end{aligned}$$

which increases in r for $r \leq \bar{x}$ and remains unchanged for $r > \bar{x}$. The upper bound of c in case of full participation is determined by the expected profit of zero before the investment decision, i.e., the expected payoff from the auction is equal to the sunk cost c, and thus before learning x_i:

$$\pi_i = \int_{\underline{x}}^{r} F(t)(1 - F_{(1,N-1)}(t))dt = c.$$

If c is still higher, then the expected profit under full participation is negative, which leads to $q = 0$. However, an equilibrium in mixed strategy may exist. That is, each firm participates with probability $q, q \in (0, 1)$. When such an equilibrium exists, it is called an equilibrium with randomized participation or endogenous entry (Jehiel and Lamy, 2015). The upper bound of c for full participation is then also the lower bound of c for endogenous participation. Define this limit value as $c^m_{min}(r)$,

$$c^m_{min}(r) := \int_{\underline{x}}^{r} F(t)(1 - F_{(1,N-1)}(t))dt. \tag{A.1}$$

The derivative is

$$\frac{dc^m_{min}(r)}{dr} = \begin{cases} F(r)(1 - F(r))^{N-1}, \text{ if } r < \bar{x}, \\ 0, \text{ if } r \geq \bar{x}. \end{cases}$$

Give the participation probability $q \in (0, 1)$, an equilibrium exists if all firms are indifferent between participating and not participating, i.e., the expected payoff is c:

$$\begin{aligned} &\pi^m = \sum_{n=0}^{N-1} P(n, q) \int_{\underline{x}}^{r} \pi(s, n) f(s) ds = c \\ &\Leftrightarrow c = P(0, q) \int_{\underline{x}}^{r} (r - s) f(s) ds + \sum_{n=1}^{N-1} P(n, q) \int_{\underline{x}}^{r} \left[\int_{s}^{r} (t - s) f_{(1,n)}(t) dt + (1 - F_{(1,n)}(r))(r - s) \right] f(s) ds \\ &\Leftrightarrow c = P(0, q) \int_{\underline{x}}^{r} F(s) ds + \sum_{n=1}^{N-1} P(n, q) \int_{\underline{x}}^{r} F(t)(1 - F_{(1,n)}(t)) dt \\ &\Leftrightarrow c = \sum_{n=0}^{N-1} P(n, q) \int_{\underline{x}}^{r} F(t)(1 - F(t))^n dt \end{aligned} \tag{A.2}$$

where

$$P(n, q) = \binom{N-1}{n} q^n (1 - q)^{N-n-1}.$$

Firms do not have an incentive to deviate from this equilibrium, because no investment means no participation, which also leads to a zero expected profit. To prove the uniqueness of q in this equilibrium, we first need to prove Lemma 2.

Proof of Lemma 2. We have

$$\frac{\partial \pi^m}{\partial r} = \sum_{n=0}^{N-1} P(n,q)\pi(r,n)f(r) > 0.$$

To prove that $\frac{\partial \pi^m}{\partial q} < 0$, we first show that $\pi(s,n)$ decreases in n:

$$\pi(s,n) = \begin{cases} r - s, \text{ if } n = 0, \\ \int_s^r (1 - F(t))^n dt, \text{ if } n \geq 1. \end{cases}$$

As $\int_s^r (1 - F(t))^n dt$ decreases in n and $\int_s^r (1 - F(t))dt < r - s$, $\pi(s,n)$ decreases in n. Thus, $\int_{\underline{x}}^r \pi(s,n)f(s)ds$ also decreases in n. Consider the expected payoff in q

$$\pi^m(q) = \sum_{n=0}^{N-1} P(n,q) \int_{\underline{x}}^r \pi(s,n)f(s)ds.$$

For $n = 0$, $P(0,q) = (1-q)^{N-1}$ decreases in $q, \forall q \in (0,1]$. For $n \in [1, N-2]$,

$$P(n,q) = \binom{N-1}{n} q^n (1-q)^{N-n-1},$$

$$\frac{\partial P(n,q)}{\partial q} = \binom{N-1}{n} q^{n-1}(1-q)^{N-n-2}[n - (N-1)q],$$

so $P(n,q)$ increases in q if $q \in [0, \frac{n}{N-1})$ and decreases in q if $q \in (\frac{n}{N-1}, 1]$, $\forall q \in (0,1]$; for $n = N-1$,$P(N-1,q) = q^{N-1}$ increases in $q, \forall q \in (0,1]$.

Consider q and $q + \Delta q$, where $\Delta q > 0$ is negligibly small. As a result, if q and $q + \Delta q$ belongs to $[\frac{i-1}{N-1}, \frac{i}{N-1}], \forall i \in [1, N-1]$, $P(n,q)$ with $n \in [0, i-1]$ decreases in q, and $P(n,q)$ with $n \in [i, N-1]$ increases in q. So we have $P(n, q+\Delta q) - P(n,q) < 0$ if $n \in [1, i-1]$ and $P(n, q+\Delta q) - P(n,q) > 0$ if $n \in [i, N-1]$. As

$$\sum_{n=0}^{N-1} P(n,q) = 1 = \sum_{n=0}^{N-1} P(n, q+\Delta q),$$

it holds that

$$\sum_{n=i}^{N-1} [P(n, q+\Delta q) - P(n,q)] = -\sum_{n=0}^{i-1} [P(n, q+\Delta q) - P(n,q)] = \Delta P > 0$$

Now, compare $\pi^m(q+\Delta q)$ with $\pi^m(q)$ by calculating $\Delta\pi^m = \pi^m(q+\Delta q) - \pi^m(q)$,

$$\begin{aligned}
&\Delta\pi^m \\
&= \sum_{n=0}^{N-1} P(n, q+\Delta q) \int_{\underline{x}}^{r} \pi(s,n) f(s) ds - \sum_{n=0}^{N-1} P(n,q) \int_{\underline{x}}^{r} \pi(s,n) f(s) ds \\
&= \sum_{n=0}^{N-1} [P(n, q+\Delta q) - P(n,q)] \int_{\underline{x}}^{r} \pi(s,n) f(s) ds \\
&= \sum_{n=0}^{i-1} [P(n, q+\Delta q) - P(n,q)] \int_{\underline{x}}^{r} \pi(s,n) f(s) ds + \sum_{n=i}^{N-1} [P(n, q+\Delta q) - P(n,q)] \int_{\underline{x}}^{r} \pi(s,n) f(s) ds \\
&\leq \sum_{n=0}^{i-1} [P(n, q+\Delta q) - P(n,q)] \int_{\underline{x}}^{r} \pi(s,i-1) f(s) ds + \sum_{n=i}^{N-1} [P(n, q+\Delta q) - P(n,q)] \int_{\underline{x}}^{r} \pi(s,i) f(s) ds \\
&= -\Delta P \int_{\underline{x}}^{r} \pi(s,i-1) f(s) ds + \Delta P \int_{\underline{x}}^{r} \pi(s,i) f(s) ds \\
&= \Delta P \int_{\underline{x}}^{r} (\pi(s,i) - \pi(s,i-1)) f(s) ds \\
&< 0.
\end{aligned}$$

Similarly, as N increases, the probability density shifts towards higher n, leading to a decrease in π^m. □

As $\frac{\partial \pi^m}{\partial q} < 0$, there is a unique q such that $\pi^m = 0$. If $q \to 1, c \to c^m_{min}(r)$. But c cannot be arbitrarily large. If c increases, q muss decrease so that $\pi^m = 0$ holds. The upper bound on c under randomized participation is that it is just worthwhile for one single firm to participate:

$$\int_{\underline{x}}^{r} (r-s) f(s) ds = \int_{\underline{x}}^{r} F(s) ds = c := c_{max}(r). \tag{A.3}$$

As c approaches $c_{max}(r)$, $q \to 0, P(0,q) \to 1$ and $\sum_{n=1}^{N-1} P(n,q) \to 0$, so that the equilibrium condition (A.2) could just still be fulfilled. That is, c_{max} is an open cap for c so that an equilibrium under randomized participation exists. Comparing Equation (A.3) with (A.1), $\forall r > \underline{x}$, it is obvious that $c_{max} > c^m_{min}(r) > 0$, which proves the first part of Lemma 1.

Proof of Lemma 3. Let $\frac{\mathbb{E}[K]-\underline{\kappa}}{\mathbb{E}[X]-\underline{x}} = \frac{\bar{\kappa}-\mathbb{E}[K]}{\bar{x}-\mathbb{E}[X]} = \sigma \in (0,1)$, since $\mathbb{E}[X] = \mathbb{E}[K]$ we have $\underline{\kappa} = (1-\sigma)\mathbb{E}[X] + \sigma\underline{x}$, $\bar{\kappa} = \sigma\bar{x} + (1-\sigma)\mathbb{E}[X]$, and $F_K(s) = F(\frac{s-\underline{\kappa}}{\sigma} + \underline{x})$.

Following Lemma 2, given N, c, and r, to prove that the participation probability is higher with F than with F_K, it is sufficient to show that $\forall n, 0 \leq n \leq N-1$,

$$\int_{\underline{x}}^{r} F(t)(1-F(t))^n dt \geq \int_{\underline{\kappa}}^{r} F_K(s)(1-F_K(s))^n ds$$
$$\Leftrightarrow \int_{\underline{x}}^{r} F(t)(1-F(t))^n dt \geq \int_{\underline{\kappa}}^{r} F(\frac{s-\underline{\kappa}}{\sigma}+\underline{x})(1-F(\frac{s-\underline{\kappa}}{\sigma}+\underline{x}))^n ds$$
$$\Leftrightarrow \int_{\underline{x}}^{r} F(t)(1-F(t))^n dt \geq \sigma \int_{\underline{x}}^{\frac{r-(1-\sigma)\mathbb{E}[X]}{\sigma}} F(t)(1-F(t))^n dt. \quad \text{(A.4)}$$

If $r \leq \mathbb{E}[X]$, then $\frac{r-(1-\sigma)\mathbb{E}[X]}{\sigma} \leq r$ and Inequality A.4 applies. Otherwise, the right side of Inequality A.4 has its maximum if $r \geq \overline{\kappa}$ while the left side increases in r for all $r \leq \bar{x}$. Since $\bar{x} > \overline{\kappa}$, a sufficient condition for Inequality A.4 is

$$\int_{\underline{x}}^{\overline{\kappa}} F(t)(1-F(t))^n dt \geq \sigma \int_{\underline{x}}^{\frac{\overline{\kappa}-(1-\sigma)\mathbb{E}[X]}{\sigma}} F(t)(1-F(t))^n dt$$
$$\Leftrightarrow (1-\sigma) \int_{\underline{x}}^{\overline{\kappa}} F(t)(1-F(t))^n dt \geq \sigma \int_{\overline{\kappa}}^{\bar{x}} F(t)(1-F(t))^n dt.$$

If $n = 0$, we have

$$(1-\sigma) \int_{\underline{x}}^{\overline{\kappa}} F(t)dt = (1-\sigma) \int_{\underline{x}}^{\bar{x}} F(t)dt - (1-\sigma) \int_{\overline{\kappa}}^{\bar{x}} F(t)dt$$
$$= (1-\sigma)(\bar{x} - \mathbb{E}[X]) - (1-\sigma) \int_{\overline{\kappa}}^{\bar{x}} F(t)dt$$
$$= (\bar{x} - \overline{\kappa}) - \int_{\overline{\kappa}}^{\bar{x}} F(t)dt + \sigma \int_{\overline{\kappa}}^{\bar{x}} F(t)dt$$
$$> \sigma \int_{\overline{\kappa}}^{\bar{x}} F(t)dt.$$

If $n \geq 1$, since $F(t)(1-F(t))^n$ increases if $F(t) < \frac{1}{n+1}$ and decreases if $F(t) > \frac{1}{n+1}$, it follows that $F(t)(1-F(t))^n$ decreases in t for $t \geq \mathbb{E}[X]$. Thus, we have

$$(1-\sigma) \int_{\underline{x}}^{\overline{\kappa}} F(t)(1-F(t))^n dt$$
$$> (1-\sigma) \int_{\mathbb{E}[X]}^{\overline{\kappa}} F(t)(1-F(t))^n dt$$
$$\geq (1-\sigma)(\overline{\kappa} - \mathbb{E}[X]) F(\overline{\kappa})(1-F(\overline{\kappa}))^n$$
$$= \sigma(\bar{x} - \overline{\kappa}) F(\overline{\kappa})(1-F(\overline{\kappa}))^n$$
$$> \sigma \int_{\overline{\kappa}}^{\bar{x}} F(t)(1-F(t))^n dt.$$

□

A.2 Proof of Proposition 2 for the voluntary setting

In the voluntary setting, each participant can either invest c and then learn the private costs x_i, or not invest and does not acquire any information other than the distribution.

A.2.1 Case $r = \mathbb{E}[X] + c$

In this case, all four equilibria with participation can exist. Note that the non-investors always have an expected profit of zero $\pi^{vn} = 0$.

Equilibrium E_1^f For $c \in [0, c^m_{min}(r)]$, the equilibrium E_1^f exists because participants expect a positive profit and therefore have no incentive to deviate from being investors to being non-investors, which would otherwise lead to an expected profit of zero.

Equilibrium E_1^r Since for all $r \geq \bar{x}$, we have $c = r - \mathbb{E}[X] = c_{max}(r)$, and $c_{max}(r)$ is an open cap for E_1^r, the equilibrium E_1^r exists for $c \in (c^m_{min}(r), \bar{x} - \mathbb{E}[X])$. The expected profit is zero, and q is the same as in the mandatory setting given $r = \mathbb{E}[X] + c$, which is determined by

$$\pi^{vi} = \sum_{n=0}^{N-1} P(n,q) \int_{\underline{x}}^{\mathbb{E}[X]+c} F(t)(1-F(t))^n dt = c. \tag{A.5}$$

Analogous to E_1^f, the participants do not have an incentive to deviate.

Equilibrium E_2 All firms choose not to invest but participate with $q' \in (0, 1]$, and $\pi^{vn} = 0$. This is an equilibrium if the one-sided deviation from non-investor to investor is not worthwhile, i.e.,

$$\int_{\underline{x}}^{\mathbb{E}[X]+c} (\mathbb{E}[X] + c - s) f(s) ds - c \leq 0 \Leftrightarrow \; c \geq \bar{x} - \mathbb{E}[X]. \tag{A.6}$$

This is because the difference on the left side decreases in c for $c \in [0, \bar{x} - \mathbb{E}[X]]$ and remains unchanged for $c > \bar{x} - \mathbb{E}[X]$. At the point $c = \bar{x} - \mathbb{E}[X]$, the difference is zero. Note that $\bar{x} - \mathbb{E}[X] > c^m_{min}(r)$:

$$c^m_{min}(r) = \int_{\underline{x}}^{r} F(t)(1-F(t))^{N-1} dt \leq \int_{\underline{x}}^{\bar{x}} F(t)(1-F(t))^{N-1} dt < \int_{\underline{x}}^{\bar{x}} F(t) dt = \bar{x} - \mathbb{E}[X].$$

As a result, for $c \geq \bar{x} - \mathbb{E}[X]$, on the line $r = \mathbb{E}[X] + c$ as well as $c_{max}(\mathbb{E}[X] + c)$, E_2 exists in the voluntary setting, while no equilibrium exists in the mandatory setting.

Equilibrium E_{mix} All firms choose to invest c with the probability q_1, not to invest but participate with the probability q_2, and not participate with the probability $1-q_1-q_2$, where $q_1 \in (0,1), q_2 \in (0,1), q_1+q_2 \leq 1$. The equilibrium E_{mix} exists if the expected profit of the investor is equal to the expected profit of the non-investor $\pi^{vi}-c=\pi^{vn}$, given that other firms follow the strategy above. As $\pi^{vn}=0$, E_{mix} requires only $\pi^{vi}=c$.

Let n_1 denote the number of investors and n_2 the number of non-investors, the corresponding probability given q_1 and q_2 is

$$\begin{aligned}P(n_1,n_2,q_1,q_2)=&\binom{N-1}{n_1+n_2}\binom{n_1+n_2}{n_1}q_1^{n_1}q_2^{n_2}(1-q_1-q_2)^{N-n_1-n_2-1}\\ =&\binom{N-1}{n_1}\binom{N-n_1-1}{n_2}q_1^{n_1}q_2^{n_2}(1-q_1-q_2)^{N-n_1-n_2-1}\end{aligned}$$

Then we have

$$\begin{aligned}&\pi^{vi}\\ =&\sum_{n_2=0}^{N-1}P(0,n_2,q_1,q_2)\int_{\underline{x}}^{\mathbb{E}[X]+c}(\mathbb{E}[X]+c-s)f(s)ds\\ &+\sum_{\substack{n_1\in[1,N-1]\\ n_2\in[0,N-1-n_1]}}P(n_1,n_2,q_1,q_2)\int_{\underline{x}}^{\mathbb{E}[X]+c}\left[\int_s^{\mathbb{E}[X]+c}(t-s)f_{(1,n_1)}(t)dt\right.\\ &\qquad\left.+(1-F_{(1,n_1)}(\mathbb{E}[X]+c))(\mathbb{E}[X]+c-s)\right]f(s)ds\\ =&\sum_{n_2=0}^{N-1}P(0,n_2,q_1,q_2)\int_{\underline{x}}^{\mathbb{E}[X]+c}F(s)ds+\sum_{n_1=1}^{N-1}\int_{\underline{x}}^{\mathbb{E}[X]+c}F(t)(1-F_{(1,n_1)}(t)dt\sum_{n_2=0}^{N-1-n_1}P(n_1,n_2,q_1,q_2).\end{aligned}$$

where

$$\sum_{n_2\in[0,N-1]}P(0,n_2,q_1,q_2)=\sum_{n_2\in[0,N-1]}\binom{N-1}{n_2}q_2^{n_2}(1-q_1-q_2)^{N-n_2-1}=(1-q_1)^{N-1}=P(0,q_1)$$

$$\begin{aligned}\sum_{n_2=0}^{N-1-n_1}P(n_1,n_2,q_1,q_2)=&\sum_{n_2=0}^{N-1-n_1}\binom{N-1}{n_1}\binom{N-n_1-1}{n_2}q_1^{n_1}q_2^{n_2}(1-q_1-q_2)^{N-n_1-n_2-1}\\ =&\binom{N-1}{n_1}q_1^{n_1}\sum_{n_2=0}^{N-1-n_1}\binom{N-n_1-1}{n_2}q_2^{n_2}(1-q_1-q_2)^{N-n_1-n_2-1}\\ =&\binom{N-1}{n_1}q_1^{n_1}(1-q_1)^{N-n_1-1}\\ =&P(n_1,q_1).\end{aligned}$$

Thus,

$$\pi^{vi} = c$$
$$\Leftrightarrow c = \sum_{n=0}^{N-1} P(n, q_1) \int_{\underline{x}}^{\mathbb{E}[X]+c} F(t)(1 - F(t))^n dt.$$

This equilibrium condition corresponds to Equation (A.5) in E_1^r and to Equation (A.2) with $r = \mathbb{E}[X] + c$ in the mandatory case. We have shown that there exists an unique q that fulfills the condition. Therefore, here we have $q_1 = q$.

This means that for each $c \in (c_{min}^m(r), \bar{x} - \mathbb{E}[X])$ where E_1^r with q exists, there exists an E_{mix} with $q_1 = q$ and any $q_2 \in (0, 1 - q]$. The reason is that q_2 has no additional influence on the expected payoff of the investors as the reserve price r. This is a special case exactly because of the equality $r = \mathbb{E}[X] + c$.

A.2.2 Case $r > \mathbb{E}[X] + c$

In this case, several equilibria can exist.

Equilibrium E_2 If all firms choosing to participate ($q' = 1$), then $\pi^{vn} = 0$. This conducts an equilibrium if the following condition is fulfilled (see also (A.6)):

$$\pi^{vi} - c = \int_{\underline{x}}^{\mathbb{E}[X]+c} (\mathbb{E}[X] + c - s) f(s) ds - c \leq \pi^{vn} = 0$$
$$\Leftrightarrow c \geq \bar{x} - \mathbb{E}[X].$$

Note that if $q' \in (0, 1)$, the expected payoff will be strictly positive so that all firms have an incentive to participate, which increases the participation probability to 1, which again lowers the expected payoff to zero. That is, the equilibrium E_2 with $q' = 1$ exists for $c \geq \bar{x} - \mathbb{E}[X]$ and $\pi^{vn} = 0$.

Equilibrium E_{mix} Note that a non-investor expects a strictly positive profit unless all other potential bidders also participate but do not invest. Thus, E_1^r (with $q \in (0, 1)$ and $\pi^{vi} = 0$) can not exist, because then each bidder has the incentive to deviate from a investor to a non-investor. However, there may exist E_{mix} with strictly positive payoff, if $\pi^{vi} - c = \pi^{vn}$, where $q_1 \in (0, 1), q_2 \in (0, 1), q_1 + q_2 = 1, n_1 + n_2 = N - 1$.

$$P(n_1, n_2, q_1, q_2) = \binom{N-1}{n_1} q_1^{n_1} (1 - q_1)^{N - n_1 - 1} = P(n_1, q_1). \tag{A.7}$$

$$
\begin{aligned}
&\pi^{vi} \\
&= P(N-1,q_1)\int_{\underline{x}}^{r}\left[\int_s^r (t-s)f_{(1,N-1)}(t)dt + (1-F_{(1,N-1)}(r))(r-s)\right]f(s)ds \\
&\quad + P(0,q_1)\int_{\underline{x}}^{\mathbb{E}[X]+c}(\mathbb{E}[X]+c-s)f(s)ds \\
&\quad + \sum_{n_1=1}^{N-2}P(n_1,q_1)\int_{\underline{x}}^{\mathbb{E}[X]+c}\left[\int_s^{\mathbb{E}[X]+c}(t-s)f_{(1,n_1)}(t)dt + (1-F_{(1,n_1)}(\mathbb{E}[X]+c))(\mathbb{E}[X]+c-s)\right]f(s)ds \\
&= P(N-1,q_1)\int_{\underline{x}}^{r}F(t)(1-F_{(1,N-1)}(t))dt + P(0,q_1)\int_{\underline{x}}^{\mathbb{E}[X]+c}F(s)ds \\
&\quad + \sum_{n_1=1}^{N-2}P(n_1,q_1)\int_{\underline{x}}^{\mathbb{E}[X]+c}F(t)(1-F_{(1,n_1)}(t))dt.
\end{aligned}
$$

$$
\begin{aligned}
\pi^{vn} = {}& P(N-1,q_1)\left[\int_{\mathbb{E}[X]+c}^{r}(t-\mathbb{E}[X]-c)f_{(1,N-1)}(t)dt + (1-F_{(1,N-1)}(r))(r-\mathbb{E}[X]-c)\right] \\
&= P(N-1,q_1)\int_{\mathbb{E}[X]+c}^{r}(1-F_{(1,N-1)}(t))dt > 0.
\end{aligned}
$$

$$
\begin{aligned}
&\Delta\pi^{v} = \pi^{vi} - c - \pi^{vn} = 0 \\
&\Leftrightarrow 0 = P(N-1,q_1)\int_{\underline{x}}^{r}F(t)(1-F_{(1,N-1)}(t))dt + P(0,q_1)\int_{\underline{x}}^{\mathbb{E}[X]+c}F(s)ds \\
&\quad + \sum_{n_1=1}^{N-2}P(n_1,q_1)\int_{\underline{x}}^{\mathbb{E}[X]+c}F(t)(1-F_{(1,n_1)}(t))dt - c - P(N-1,q_1)\int_{\mathbb{E}[X]+c}^{r}(1-F_{(1,N-1)}(t))dt.
\end{aligned}
$$

$$
\Leftrightarrow \sum_{n_1=0}^{N-1}P(n_1,q_1)\int_{\underline{x}}^{\mathbb{E}[X]+c}F(t)(1-F(t))^{n_1}dt - P(N-1,q_1)\int_{\mathbb{E}[X]+c}^{r}(1-F(t))^{N}dt - c = 0. \quad (A.8)
$$

$\Delta\pi^v > 0$ means that investment is preferred to non-investment. $\Delta\pi^v < 0$ means that non-investment is preferred to investment. Thus, a higher $\Delta\pi^v$ speaks in favor of investment. Since $\pi^{vi} > 0 = \pi^m$, given the same c and r, the participation probability q_1 must be smaller than the participation probability q in the mandatory setting.

Proof of Lemma 4. We have $\frac{\partial \Delta\pi^v}{\partial r} = -P(N-1,q_1)(1-F(r))^N < 0$ and

$$\begin{aligned}
\frac{\partial \Delta\pi^v}{\partial c} &= \sum_{n_1=0}^{N-1} P(n_1,q_1)F(\mathbb{E}[X]+c)(1-F(\mathbb{E}[X]+c))^{n_1}dt + P(N-1,q_1)(1-F(\mathbb{E}[X]+c))^N dt - 1 \\
&= \sum_{n_1=0}^{N-2} P(n_1,q_1)F(\mathbb{E}[X]+c)(1-F(\mathbb{E}[X]+c))^{n_1}dt + P(N-1,q_1)(1-F(\mathbb{E}[X]+c))^{N-1} \\
&\quad - \sum_{n_1=0}^{N-1} P(n_1,q_1) \\
&< 0.
\end{aligned}$$

Analogous to the proof of Lemma 2, the first term in Equation (A.8) decreases in q_1, and the second term decreases in q_1 obviously, thus, $\frac{\partial \Delta\pi^v}{\partial q_1} < 0$. Similarly, as N increases, the probability density shifts towards higher n_1, leading to a decrease in $\Delta\pi^v$.

Therefore, $\frac{dq_1}{dr} < 0$, $\frac{dq_1}{dc} < 0$, and $\frac{dq_1}{dN} < 0$. That is, the higher r, c, or N is, the lower is $\Delta\pi^v$ and thus in favor of non-investment and a lower q_1. □

As $\frac{\partial \Delta\pi^v}{\partial q_1} < 0$, there exists a unique q_1 that satisfies Equation (A.8). As a result, the equilibrium E_{mix} yields q_1 determined by Equation (A.8), $q_2 = 1-q_1$ for $c \in (c^v_{min}(r), \bar{x}-\mathbb{E}[X])$, and $\pi^{vn} = \pi^{vi} > 0$.

Due to the monotonicity of $\Delta\pi^v$ in q_1, the upper and lower limits of c can be determined by $q \Rightarrow 0$ and $q \Rightarrow 1$, respectively. If $q_1 \to 0, c \to \bar{x} - \mathbb{E}[X] = c_{max}(r)$; if $q_1 \to 1$,

$$c \to \int_{\underline{x}}^{\mathbb{E}[X]+c} F(t)(1-F_{(1,N-1)}(t))dt - \int_{\mathbb{E}[X]+c}^{r} (1-F_{(1,N)}(t))dt \tag{A.9}$$

$$= \int_{\underline{x}}^{r} F(t)(1-F_{(1,N-1)}(t))dt - \int_{\mathbb{E}[X]+c}^{r} (1-F_{(1,N-1)}(t))dt := c^v_{min}(r). \tag{A.10}$$

Proof of Lemma 1. It is obvious that $c^v_{min}(r) < c^m_{min}(r) < c_{max}(r)$ for $r > \mathbb{E}[X]+c$, and $c^v_{min}(\mathbb{E}[X]+c) = c^m_{min}(\mathbb{E}[X]+c)$. Since $\frac{\partial c^v_{min}(r)}{\partial r} = -(1-F(r))^N \leq 0$, $c^v_{min}(r)$ decreases in r for $r \leq \bar{x}$ and is constant for $r > \bar{x}$, so $c^v_{min}(r)$ has its minimum at $r = \bar{x}$. To prove $c^v_{min}(r) > 0$, it is sufficient to show $c^v_{min}(\bar{x}) > 0$. Let

$$I(c) = \int_{\underline{x}}^{\bar{x}} F(t)(1-F_{(1,N-1)}(t))dt - \int_{\mathbb{E}[X]+c}^{\bar{x}} (1-F_{(1,N-1)}(t))dt - c.$$

Since $\frac{dI(c)}{dc} = (1-F(\mathbb{E}[X]+c))^{N-1} - 1 < 0$, $I(c)$ decreases in c. We have $I(c^m_{min}(\bar{x})) = -\int_{\mathbb{E}[X]+c^m_{min}(\bar{x})}^{\bar{x}} (1-F_{(1,N-1)}(t))dt < 0$ and $I(0) = \int_{\underline{x}}^{\bar{x}} F(t)(1-F_{(1,N-1)}(t))dt - \int_{\mathbb{E}[X]}^{\bar{x}}(1-F_{(1,N-1)}(t))dt$. If $I(0) > 0$, we can conclude that $0 < c^v_{min}(\bar{x}) < c^m_{min}(\bar{x})$.

The first term in $I(0)$, $\int_{\underline{x}}^{\bar{x}} F(t)(1-F_{(1,N-1)}(t))dt$, corresponds to the a priori (i.e., before bidders learn their private costs) expected profit of a bidder in a second-price auction without a reserve price, assuming all bidders bid their true private costs after learning them. The second term, $\int_{\mathbb{E}[X]}^{\bar{x}}(1 - F_{(1,N-1)}(t))dt$, corresponds to the a priori expected profit of a bidder who bids a fixed value equal to $\mathbb{E}[X]$ in a second-price auction without a reserve price, while all other bidders bid their true private costs after learning them. Since truthful bidding is the unique weakly dominant strategy in a second-price auction without a reserve price, the expected profit from bidding one's true private cost is strictly higher than that from bidding $\mathbb{E}[X]$, regardless of the actual private cost realization. As a result, the a priori expected profit is also strictly higher in the truthful bidding case, implying that $I(0)$ is strictly positive. □

This result is plausible because the advantage of investors over non-investors is strictly positive at $c = 0$. Besides, we have

$$\begin{aligned}\frac{\partial I(0)}{\partial N} &= \int_{\underline{x}}^{\bar{x}} F(t)(1 - F_{(1,N-1)}(t)) \ln(1 - F(t))dt - \int_{\mathbb{E}[X]}^{\bar{x}}(1 - F_{(1,N-1)}(t)) \ln(1 - F(t))dt \\ &= \int_{\underline{x}}^{\mathbb{E}[X]} F(t)(1 - F(t))^{N-1} \ln(1 - F(t))dt - \int_{\mathbb{E}[X]}^{\bar{x}}(1 - F(t))^{N} \ln(1 - F(t))dt \\ &< \int_{\underline{x}}^{\mathbb{E}[X]} F(t)(1 - F(t))^{N-1} \ln(1 - F(\mathbb{E}[X]))dt - \int_{\mathbb{E}[X]}^{\bar{x}}(1 - F(t))^{N} \ln(1 - F(\mathbb{E}[X]))dt \\ &= \ln(\frac{1}{2})I(0) < 0.\end{aligned}$$

The higher N, the lower is $I(0)$, and thus the lower is $c^{v}_{min}(\bar{x})$. In other words, with more competition, full participation requires a lower c. For instance, under uniform distribution, we have $F(x) = x$, $I(0) = \frac{1}{N}(\frac{1}{N+1} - (\frac{1}{2})^N)$, which is strictly positive for $N \geq 2$ and decreases in N.

Proof of Lemma 5. Let $\frac{\mathbb{E}[K]-\underline{\kappa}}{\mathbb{E}[X]-\underline{x}} = \frac{\bar{\kappa}-\mathbb{E}[K]}{\bar{x}-\mathbb{E}[X]} = \sigma \in (0,1)$, since $\mathbb{E}[X] = \mathbb{E}[K]$ we have $\underline{\kappa} = (1-\sigma)\mathbb{E}[X] + \sigma\underline{x}$, $\bar{\kappa} = \sigma\bar{x} + (1-\sigma)\mathbb{E}[X]$, and $F_K(s) = F(\frac{s-\underline{\kappa}}{\sigma} + \underline{x})$.

If $\mathbb{E}[X] + c \geq \bar{\kappa}$, there will only be non-investors in the equilibrium, so the investment probability is zero with F_K, while $q_1 > 0$ with F.

If $\mathbb{E}[X] + c \geq \bar{\kappa}$, with both F and F_K, the investment probability is positive. Following Lemma 2 and 4, given N, c, and r, to prove that under F_K the probability of participation corresponding q_1 is less than q_1, it is sufficient to show that

$$\begin{aligned}&\int_{\underline{x}}^{\mathbb{E}[X]+c} F(t)(1 - F(t))^{N-1}dt - \int_{\mathbb{E}[X]+c}^{r}(1 - F(t))^{N}dt \\ \geq &\int_{\underline{\kappa}}^{\mathbb{E}[X]+c} F_K(s)(1 - F_K(s))^{N-1}ds - \int_{\mathbb{E}[X]+c}^{r}(1 - F_K(s))^{N}ds.\end{aligned}$$

Analogous to Lemma 3, since $r > \mathbb{E}[X] + c$ and $\frac{\partial \Delta\pi^v}{\partial r} < 0$, a sufficient condition is to show that the above inequality applies if $r = \bar{x}$, i.e.,

$$
\begin{aligned}
&\int_{\underline{x}}^{\mathbb{E}[X]+c} F(t)(1-F(t))^{N-1}dt - \int_{\mathbb{E}[X]+c}^{\bar{x}} (1-F(t))^{N}dt \\
&\geq \int_{\underline{\kappa}}^{\mathbb{E}[X]+c} F_K(s)(1-F_K(s))^{N-1}ds - \int_{\mathbb{E}[X]+c}^{\bar{x}} (1-F_K(s))^{N}ds \\
\Leftrightarrow &\int_{\underline{x}}^{\bar{x}} F(t)(1-F(t))^{N-1}dt - \int_{\mathbb{E}[X]+c}^{\bar{x}} (1-F(t))^{N-1}dt \\
&\geq \int_{\underline{\kappa}}^{\overline{\kappa}} F_K(s)(1-F_K(s))^{N-1}ds - \int_{\mathbb{E}[X]+c}^{\overline{\kappa}} (1-F_K(s))^{N-1}ds \\
\Leftrightarrow &\int_{\underline{x}}^{\bar{x}} F(t)(1-F(t))^{N-1}dt - \int_{\mathbb{E}[X]+c}^{\bar{x}} (1-F(t))^{N-1}dt \\
&\geq \sigma \int_{\underline{x}}^{\bar{x}} F(t)(1-F(t))^{N-1}dt - \sigma \int_{\mathbb{E}[X]+\frac{c}{\sigma}}^{\bar{x}} (1-F(t))^{N-1}dt \\
\Leftrightarrow &(1-\sigma)\left[\int_{\underline{x}}^{\bar{x}} F(t)(1-F(t))^{N-1}dt - \int_{\mathbb{E}[X]+c^v_{min}(\bar{x})}^{\bar{x}} (1-F(t))^{N-1}dt\right] \\
&+ \int_{\mathbb{E}[X]+c^v_{min}(\bar{x})}^{\mathbb{E}[X]+c} (1-F(t))^{N-1}dt \ -\sigma \int_{\mathbb{E}[X]+c^v_{min}(\bar{x})}^{\mathbb{E}[X]+\frac{c}{\sigma}} (1-F(t))^{N-1}dt \geq 0 \\
\Leftrightarrow &(1-\sigma)c^v_{min}(\bar{x}) + (1-\sigma)\int_{\mathbb{E}[X]+c^v_{min}(\bar{x})}^{\mathbb{E}[X]+c} (1-F(t))^{N-1}dt - \sigma \int_{\mathbb{E}[X]+c}^{\mathbb{E}[X]+\frac{c}{\sigma}} (1-F(t))^{N-1}dt \geq 0 \\
\Leftarrow &(1-\sigma)c^v_{min}(\bar{x}) + (1-\sigma)(c - c^v_{min}(\bar{x}))(1-F(\mathbb{E}[X]+c))^{N-1} \\
&-\sigma(\frac{c}{\sigma} - c)(1-F(\mathbb{E}[X]+c))^{N-1} \geq 0 \\
\Leftrightarrow &(1-\sigma)c^v_{min}(\bar{x})(1-(1-F(\mathbb{E}[X]+c))^{N-1}) \geq 0.
\end{aligned}
$$

□

Equilibrium E_1^f As c approaches zero, the advantage of investors against investors is so large that all firms will participate and invest, so E_1^f exists. The upper bound of c for E_1^f is determined by the scenario that if all $N-1$ other firms participate and invest, the considered firm will participate and is indifferent between investing and not investing.

$$
\begin{aligned}
\pi^{vi} &= \int_{\underline{x}}^{r} \left[\int_{s}^{r} (t-s)f_{(1,N-1)}(t)dt + (1-F_{(1,N-1)}(r))(r-s)\right] f(s)ds \\
&= \int_{\underline{x}}^{r} F(t)(1-F_{(1,N-1)}(t))dt.
\end{aligned}
$$

$$\begin{aligned}\pi^{vn} &= \int_{\mathbb{E}[X]+c}^{r} (t - \mathbb{E}[X] - c) f_{(1,N-1)}(t)dt + (1 - F_{(1,N-1)}(r))(r - \mathbb{E}[X] - c)\\ &= \int_{\mathbb{E}[X]+c}^{r} (1 - F_{(1,N-1)}(t))dt.\end{aligned}$$

$$\pi^{vi} = \pi^{vn} - c \Leftrightarrow c = \int_{\underline{x}}^{r} F(t)(1 - F_{(1,N-1)}(t))dt - \int_{\mathbb{E}[X]+c}^{r} (1 - F_{(1,N-1)}(t))dt = c^{v}_{min}(r).$$

As a result, the equilibrium E_1^f exists for $c \in [0, c^v_{min}(r)]$.

A.3 Comparison under reserve price in general

Proof of Proposition 3. To compare the expected participation and investment level in both settings, the following three cases are considered:

In case $r = \mathbb{E}[X] + c$, the voluntary setting allows the participation of non-investors in addition to the investors in the mandatory setting, leading to a higher expected participation, while the expected a priori investment level remains the same. That is, $0 \leq q_1 = q \leq q_1 + q_2 \leq 1$ if $c < \bar{x} - \mathbb{E}[X]$, and $0 = q \leq q' = 1$ if $c \geq \bar{x} - \mathbb{E}[X]$.

In case $r > \mathbb{E}[X] + c$ and $c \in (c^v_{min}(r), c^m_{min}(r)]$, both settings lead to full participation. While in the mandatory setting all participants invest, in the voluntary setting the participants invest with the probability q_1. That is, $0 < q_1 < q = q_1 + q_2 = 1$.

In case $r > \mathbb{E}[X] + c$ and $c > c^m_{min}(r)$, the voluntary setting leads to full participation (N participants) while the mandatory setting leads to randomized participation with $Nq < N$ expected participants. That is, $0 < q_1 < q < q_1 + q_2 = 1$ if $c < \bar{x} - \mathbb{E}[X]$, and $0 < q < q' = 1$ if $c \geq \bar{x} - \mathbb{E}[X]$. □

Proof of Proposition 4. In the symmetric equilibria in both settings, participant's expected profits are positive in E_1^f and E_{mix}, and zero in E_1^r and E_2.

In case $r > \mathbb{E}[X]+c$ and $c \in (c^v_{min}(r), c^m_{min}(r))$, both E_1^f in the mandatory setting and E_{mix} in the voluntary setting result in full participation and $q > q_1$. Although total participation is identical in both settings, a higher share of investors lowers the expected value of the first-order statistic, i.e. the expected lowest cost among investors, while the expected costs of non-investors remain fixed at $\mathbb{E}[X] + c$. Thus, the increased share of investors leads to more intense competition within the auction. As a result, investors in the mandatory setting expect lower expected profits compared to the voluntary setting. □

A.4 Comparison under efficient reserve price

Proof of Proposition 5. A SA with $r = x_0$ maximizes the expected welfare and implements the (interim) efficient mechanism. In the following, we compare the expected welfare under $r = x_0$ in both settings and differentiate the areas marked in Figure A.1.

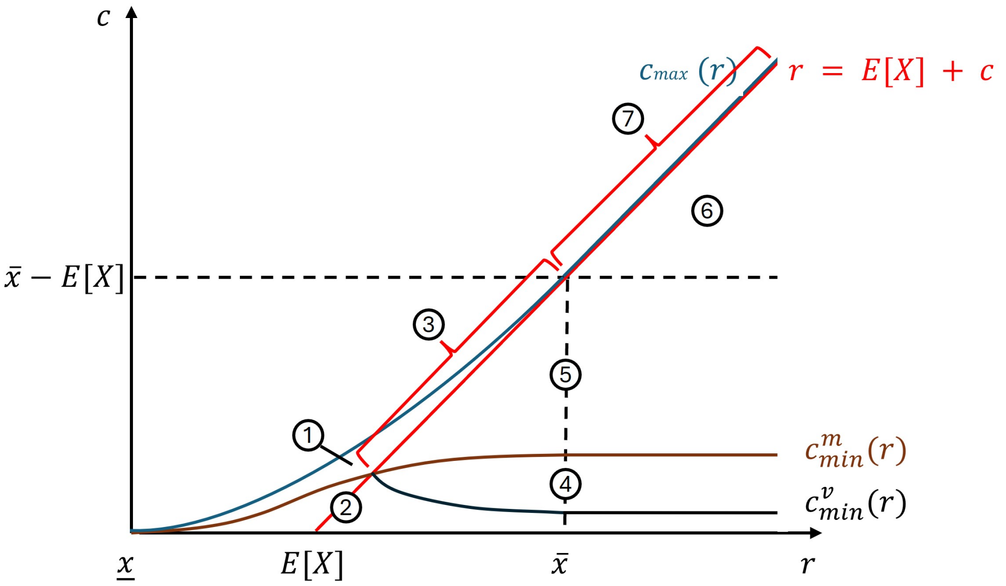

Figure A.1: Division and numbering of the relevant areas

A.4.1 Area 1 with $r < \mathbb{E}[X] + c$ and $c > c^m_{min}(r)$

The equilibrium E^r_1 is the same in both mandatory and voluntary settings, so the expected welfare is also the same.

A.4.2 Area 2 with $c \leq c^m_{min}(r)$ if $r \leq \mathbb{E}[X] + c$ and $c \leq c^v_{min}(r)$ if $r > \mathbb{E}[X] + c$

Equilibrium E^f_1 is the same in both the mandatory and voluntary settings, therefore, the expected welfare is also the same.

A.4.3 Area 3 with $r = x_0 = \mathbb{E}[X] + c$ and $c^v_{min}(r) = c^m_{min}(r) < c < \bar{x} - \mathbb{E}[X]$

In the mandatory setting, equilibrium E^r_1 yields the following expected welfare:

$$W^m = \sum_{n=1}^{N} P_A(n,q) \left[\int_{\underline{x}}^{x_0} (x_0 - t) f_{(1,n)}(t)dt - n \cdot c \right] = \sum_{n=1}^{N} P_A(n,q) \int_{\underline{x}}^{x_0} F_{(1,n)}(t)dt - Nqc.$$

where

$$P_A(n,q) = \binom{N}{n} q^n (1-q)^{N-n},$$

$$nP_A(n,q) = NqP(n-1,q),$$

and

$$\sum_{n=1}^{N} nP_A(n,q) = Nq \sum_{n=0}^{N-1} P(n,q) = Nq.$$

In the equilibria in the voluntary setting, $q_1 = q$ and $q_2 \in [0, 1-q]$. If $q_2 = 0$, the equilibrium E_1^r is the same as in the mandatory case, thus yields the same expected welfare. If $q_2 \in (0, 1-q)$, the equilibrium E_{mix} yields the expected welfare

$$\begin{aligned}
W^v = &\sum_{n_1=1}^{N} P_A(n_1, 0, q_1, q_2) \left[\int_{\underline{x}}^{x_0} (x_0 - t) f_{(1,n_1)}(t)dt - n_1 c \right] \\
&+ \sum_{n_2=1}^{N} P_A(0, n_2, q_1, q_2)(x_0 - \mathbb{E}[X] - c) \\
&+ \sum_{\substack{n_1 \in [1,N-1] \\ n_2 \in [1,N-n_1]}} P_A(n_1, 0, q_1, q_2) \left[\int_{\underline{x}}^{x_0} (x_0 - t) f_{(1,n_1)}(t)dt - n_1 c + (1 - F_{(1,n_1)}(x_0))(x_0 - \mathbb{E}[X] - c) \right] \\
= &\sum_{n_1=1}^{N} \sum_{n_2=0}^{N-n_1} P_A(n_1, n_2, q_1, q_2) \left[\int_{\underline{x}}^{x_0} (x_0 - t) f_{(1,n_1)}(t)dt - n_1 c \right] \\
= &\sum_{n_1=1}^{N} P_A(n_1, q_1) \left[\int_{\underline{x}}^{x_0} (x_0 - t) f_{(1,n_1)}(t)dt - n_1 c \right] = W^m,
\end{aligned}$$

where

$$P_A(n_1, n_2, q_1, q_2) = \binom{N}{n_1} \binom{N-n_1}{n_2} q_1^{n_1} q_2^{n_2} (1 - q_1 - q_2)^{N-n_1-n_2},$$

and

$$\sum_{n_2=0}^{N-n_1} P_A(n_1, n_2, q_1, q_2) = P_A(n_1, q_1) = \binom{N}{n} q^n (1-q)^{N-n},$$

analog to E_{mix} in case 2 in the voluntary setting.

As a result, regardless of q_2, the expected welfare is always the same in mandatory and voluntary settings.

A.4.4 Area 4 with $r = x_0 > \mathbb{E}[X] + c$ and $c \in (c^v_{min}(r), c^m_{min}(r))$

In the mandatory setting, E_1^f yields the expected welfare

$$W^m = \int_{\underline{x}}^{x_0} (x_0 - t) f_{(1,N)}(t)dt - N \cdot c = \int_{\underline{x}}^{x_0} F_{(1,N)}(t)dt - Nc.$$

In the voluntary setting, E_{mix} with $q_1 \in (0,1)$ and $q_2 = 1 - q_1$ yields the expected welfare

$$\begin{aligned}
&W^v \\
=&P_A(N,q_1)\int_{\underline{x}}^{x_0}(x_0-t)f_{(1,N)}(t)dt - P_A(N,q_1)Nc + P_A(0,q_1)(x_0-\mathbb{E}[X]-c) \\
&+\sum_{n_1=1}^{N-1}P_A(n_1,q_1)\left[\int_{\underline{x}}^{\mathbb{E}[X]+c}(x_0-t)f_{(1,n_1)}(t)dt - n_1c + (1-F(\mathbb{E}[X]+c))^{n_1}(x_0-\mathbb{E}[X]-c)\right] \\
=&P_A(N,q_1)\int_{\underline{x}}^{x_0}F_{(1,N)}(t)dt + \sum_{n_1=1}^{N-1}P_A(n_1,q_1)\int_{\underline{x}}^{\mathbb{E}[X]+c}F_{(1,n_1)}(t)dt \\
&+(1-P_A(N,q_1))(x_0-\mathbb{E}[X]-c) - Nq_1c,
\end{aligned}$$

where

$$c = \sum_{n_1=0}^{N-1}P(n_1,q_1)\int_{\underline{x}}^{\mathbb{E}[X]+c}F(t)(1-F(t))^{n_1}dt - P(N-1,q_1)\int_{\mathbb{E}[X]+c}^{r}(1-F(t))^N dt,$$

$$\begin{aligned}
&Nq_1c \\
=&\sum_{n_1=0}^{N-1}Nq_1P(n_1,q_1)\int_{\underline{x}}^{\mathbb{E}[X]+c}F(t)(1-F(t))^{n_1}dt - Nq_1P(N-1,q_1)\int_{\mathbb{E}[X]+c}^{r}(1-F(t))^N dt \\
=&\sum_{n=1}^{N}P_A(n,q_1)\int_{\underline{x}}^{\mathbb{E}[X]+c}nF(t)(1-F(t))^{n-1}dt - P_A(N,q_1)\int_{\mathbb{E}[X]+c}^{x_0}N(1-F(t))^N dt.
\end{aligned}$$

The welfare difference is

$$\begin{aligned}
&\Delta W = W^v - W^m \\
=&\ P_A(N,q_1)\int_{\underline{x}}^{x_0}F_{(1,N)}(t)dt + \sum_{n_1=1}^{N-1}P_A(n_1,q_1)\int_{\underline{x}}^{\mathbb{E}[X]+c}F_{(1,n_1)}(t)dt + (1-P_A(N,q_1))(x_0-\mathbb{E}[X]-c) \\
&-\int_{\underline{x}}^{x_0}F_{(1,N)}(t)dt + Nc - \sum_{n=1}^{N}P_A(n,q_1)\int_{\underline{x}}^{\mathbb{E}[X]+c}nF(t)(1-F(t))^{n-1}dt \\
&+P_A(N,q_1)\int_{\mathbb{E}[X]+c}^{x_0}N(1-F(t))^N dt \\
=&\ P_A(N,q_1)\int_{\underline{x}}^{x_0}F_{(1,N)}(t)dt - P_A(N,q_1)\int_{\underline{x}}^{\mathbb{E}[X]+c}F_{(1,N)}(t)dt + \sum_{n=2}^{N}P_A(n,q_1)\int_{\underline{x}}^{\mathbb{E}[X]+c}F_{(2,n)}(t)dt \\
&+(1-P_A(N,q_1))(x_0-\mathbb{E}[X]-c) - \int_{\underline{x}}^{x_0}F_{(1,N)}(t)dt + Nc + P_A(N,q_1)\int_{\mathbb{E}[X]+c}^{x_0}N(1-F(t))^N dt.
\end{aligned}$$

If $x_0 \geq \bar{x}$,

$$\Delta W = P_A(N,q_1)\int_{\underline{x}}^{\bar{x}} F_{(1,N)}(t)dt - P_A(N,q_1)\int_{\underline{x}}^{\mathbb{E}[X]+c} F_{(1,N)}(t)dt + \sum_{n=1}^{N} P_A(n,q_1)\int_{\underline{x}}^{\mathbb{E}[X]+c} F_{(2,n)}(t)dt$$
$$+ (1-P_A(N,q_1))(\bar{x}-\mathbb{E}[X]-c) - \int_{\underline{x}}^{\bar{x}} F_{(1,N)}(t)dt + Nc + P_A(N,q_1)\int_{\mathbb{E}[X]+c}^{\bar{x}} N(1-F(t))^N dt,$$

$$\begin{aligned}\frac{\partial \Delta W}{\partial c} =& -P_A(N,q_1)F_{(1,N)}(\mathbb{E}[X]+c) + \sum_{n=1}^{N} P_A(n,q_1)F_{(2,n)}(\mathbb{E}[X]+c) - (1-P_A(N,q_1)) + N \\ & - P_A(N,q_1)N(1-F(\mathbb{E}[X]+c))^N \\ \geq & -P_A(N,q_1)F_{(1,N)}(\mathbb{E}[X]+c) - (1-P_A(N,q_1)) + N - P_A(N,q_1)N(1-F(\mathbb{E}[X]+c))^N \\ =& -q_1^N(1-(1-F(\mathbb{E}[X]+c))^N) - 1 + q_1^N + N - q_1^N N(1-F(\mathbb{E}[X]+c))^N \\ =& \, q_1^N(1-F(\mathbb{E}[X]+c))^N) - 1 + N - q_1^N N(1-F(\mathbb{E}[X]+c))^N \\ =& \,(N-1)(1-q_1^N(1-F(\mathbb{E}[X]+c))^N)) \\ \geq & \, 0,\end{aligned}$$

Thus, ΔW has its minimum when $c = c^v_{min}(\bar{x})$. Since $q_1 = 1$ at $c = c^v_{min}(\bar{x})$, we have $\Delta W = 0$. Therefore, $\Delta W \geq 0$ if $x_0 \geq \bar{x}$.

If $x_0 < \bar{x}$, we have

$$\begin{aligned}&\Delta W(x_0,c,q_1) \\ &= P_A(N,q_1)\int_{\underline{x}}^{\bar{x}} F_{(1,N)}(t)dt - P_A(N,q_1)\int_{\underline{x}}^{\mathbb{E}[X]+c} F_{(1,N)}(t)dt + \sum_{n=2}^{N} P_A(n,q_1)\int_{\underline{x}}^{\mathbb{E}[X]+c} F_{(2,n)}(t)dt \\ &\quad + (1-P_A(N,q_1))(\bar{x}-\mathbb{E}[X]-c) - \int_{\underline{x}}^{\bar{x}} F_{(1,N)}(t)dt + Nc + P_A(N,q_1)\int_{\mathbb{E}[X]+c}^{\bar{x}} N(1-F(t))^N dt \\ &\quad - (1+P_A(N,q_1)(N-1))\int_{x_0}^{\bar{x}}(1-F(t))^N dt \\ &= P_A(N,q_1)\int_{\mathbb{E}[X]+c}^{\bar{x}}(N-1)(1-F(t))^N dt + \sum_{n=2}^{N} P_A(n,q_1)\int_{\underline{x}}^{\mathbb{E}[X]+c} F_{(2,n)}(t)dt + (\bar{x}-\mathbb{E}[X]-c) \\ &\quad + Nc - \int_{\underline{x}}^{\bar{x}} F_{(1,N)}(t)dt - (1+P_A(N,q_1)(N-1))\int_{x_0}^{\bar{x}}(1-F(t))^N dt,\end{aligned}$$

subject to

$$\begin{aligned}&\Delta\pi^v(x_0,c,q_1) \\ &= \sum_{n_1=0}^{N-1} P(n_1,q_1)\int_{\underline{x}}^{\mathbb{E}[X]+c} F(t)(1-F(t))^{n_1}dt - P(N-1,q_1)\int_{\mathbb{E}[X]+c}^{r}(1-F(t))^N dt - c = 0.\end{aligned}$$

To find the minimum of ΔW, we have the following minimizing problem with Lagrange-multiplicand λ and the Karush-Kuhn-Tucker (KKT) conditions with factors $\mu_1 \geq 0$ and $\mu_2 \geq 0$ for $q_1 \in (0,1]$:

$$\min_{x_0,c,q_1} L(x_0,c,q_1,\lambda,\mu_1,\mu_2) := \Delta W(x_0,c,q_1) + \lambda\Delta\pi^v(x_0,c,q_1) + \mu_1(-q_1) + \mu_2(q_1-1)$$

$$s.t.\ \frac{\partial L}{\partial x_0} = (1+P_A(N,q_1)(N-1))(1-F(x_0))^N - \lambda P(N-1,q_1)(1-F(x_0))^N = 0 \quad \text{(A.11)}$$

$$\frac{\partial L}{\partial c} = (N-1)(1-P_A(N,q_1)(1-F(\mathbb{E}[X]+c))^N) + \sum_{n=2}^{N} P_A(n,q_1)F_{(2,n)}(\mathbb{E}[X]+c)$$
$$+ \lambda \left[\sum_{n_1=0}^{N-1} P(n_1,q_1)F(\mathbb{E}[X]+c)(1-F(\mathbb{E}[X]+c))^{n_1} \right.$$
$$\left. + P(N-1,q_1)(1-F(\mathbb{E}[X]+c))^N - 1\right] = 0 \quad \text{(A.12)}$$

$$\frac{\partial L}{\partial q_1} = \frac{\partial \Delta W}{\partial q_1} + \lambda\frac{\partial \Delta\pi^v}{\partial q_1} - \mu_1 + \mu_2 = 0 \quad \text{(A.13)}$$

$$\Delta\pi^v(x_0,c,q_1) = 0$$
$$-q_1 \leq 0$$
$$q_1 - 1 \leq 0$$
$$\mu_1(-q_1) = 0$$
$$\mu_2(q_1-1) = 0$$

Constraint (A.11) leads to $x_0 = \bar{x}$ or $\lambda = (N-1)q_1 + \frac{1}{q_1^{N-1}}$, note than in this case $q_1 > 0$. $x_0 = \bar{x}$ is a boundary case, which has already be considered above (in case $x_0 \geq \bar{x}$) and we have shown that $\Delta W \geq 0$ if $x_0 = \bar{x}$. Now, let's substitute $\lambda = (N-1)q_1 + \frac{1}{q_1^{N-1}}$ in constraint (A.12), which can be simplified to

$$\begin{aligned}
\frac{\partial L}{\partial c} =& N - (N-1)q_1^N(1-F(\mathbb{E}[X]+c))^N - (1-q_1F(\mathbb{E}[X]+c))^N \\
& - Nq_1F(\mathbb{E}[X]+c)(1-q_1F(\mathbb{E}[X]+c))^{N-1} \\
& + \lambda\left[F(\mathbb{E}[X]+c)(1-q_1F(\mathbb{E}[X]+c))^{N-1} + q_1^{N-1}(1-F(\mathbb{E}[X]+c))^{N-1} - 1\right] \\
=& N - (1-q_1F(\mathbb{E}[X]+c))^{N-1} + F(\mathbb{E}[X]+c)(\frac{1}{q_1} - F(\mathbb{E}[X]+c))^{N-1} \\
& + (1-F(\mathbb{E}[X]+c))^N - (N-1)q_1 - \frac{1}{q_1^{N-1}},
\end{aligned}$$

where

$$\sum_{n_1=0}^{N-1} P(n_1, q_1)(1-D)^{n_1} = \sum_{n_1=0}^{N-1} \binom{N-1}{n_1} (q_1(1-D))^{n_1}(1-q_1)^{N-n_1-1}$$
$$=(q_1(1-D)+1-q_1)^{N-1} = (1-q_1T)^{N-1},$$

$$\sum_{n=0}^{N} P_A(n,q)(1-D)^n = (1-qT)^N$$
$$\Rightarrow \sum_{n=0}^{N} \binom{N}{n} q^{n-1}(1-q)^{N-n-1}(n-Nq)(1-D)^n = -NT(1-qT)^{N-1}$$
$$\Rightarrow \sum_{n=0}^{N} \binom{N}{n} q^{n-1}(1-q)^{N-n-1} n(1-D)^n$$
$$= N\sum_{n=0}^{N} \binom{N}{n} q^{n}(1-q)^{N-n-1}(1-D)^n - NT(1-qT)^{N-1}$$
$$\Rightarrow \sum_{n=0}^{N} \binom{N}{n} q^{n}(1-q)^{N-n} n(1-D)^n = q(1-q)[\frac{N}{1-q}(1-qT)^N - NT(1-qT)^{N-1}]$$
$$\Rightarrow \sum_{n=0}^{N} \binom{N}{n} q^{n}(1-q)^{N-n} nT(1-D)^{n-1} = Nq(1-qT)^{N-1}D,$$

$$\sum_{n=2}^{N} P_A(n,q_1)F_{(2,n)}(\mathbb{E}[X]+c)$$
$$=\sum_{n=0}^{N} P_A(n,q_1)F_{(2,n)}(\mathbb{E}[X]+c)$$
$$=\sum_{n=0}^{N} P_A(n,q_1)(1-(1-F(\mathbb{E}[X]+c))^N - NF(\mathbb{E}[X]+c)(1-F(\mathbb{E}[X]+c))^{N-1})$$
$$=1-(1-q_1F(\mathbb{E}[X]+c))^N - Nq_1F(\mathbb{E}[X]+c)(1-q_1F(\mathbb{E}[X]+c))^{N-1}.$$

Deviate $\frac{\partial L}{\partial c}$ by q_1, it holds that

$$\frac{\partial^2 L}{\partial c \partial q_1} = (N-1)(\frac{1}{q_1^N}-1)(1-F(\mathbb{E}[X]+c)(1-q_1F(\mathbb{E}[X]+c))^{N-1}) \geq 0.$$

So $\frac{\partial L}{\partial c}$ has its maximum at $q_1 = 1$, which is 0. Given $q_1 = 1$, the minimizing problem has the following KKT points: $q_1 = 1, \lambda = N, \mu_1 = 0$, $c = c^v_{min}(x_0)$, μ_2 depends on x_0 according to Constraint (A.13) and x_0 arbitrary. These points are on the lower boundary. Thus, there exists no internal minimum or maximum. Next, we compare all ΔW on the boundary: If $x_0 = \bar{x}$, as mentions above, $\Delta W \geq 0$ and increases in c; if $x_0 = \int_{\underline{x}}^{x_0} F(t)(1-F(t))^{N-1}dt, \Delta W = 0$; if $q_1 = 1$, that is $c = c^v_{min}(x_0), \Delta W = 0$; if q_1 is minimal, that is $x_0 = \bar{x}$ and $c = c^m_{min}(\bar{x})$ according to Lemma 4, $\Delta W > 0$; if $c = c^v_{min}(x_0), \Delta W = 0$; if $c = c^m_{min}(x_0) := \tilde{c}$, substitute c in ΔW and we have

$$\begin{aligned}\frac{\partial \Delta W}{\partial x_0} =&(1 + P_A(N,q_1)(N-1))(1-F(x_0))^N \\ &+ \sum_{n_1=2}^{N} P_A(n_1,q_1)F_{(2,n_1)}(\mathbb{E}[X]+\tilde{c})F(x_0)(1-F(x_0))^{N-1} \\ &+ (N-1)(1-P_A(N,q_1)(1-F(\mathbb{E}[X]+\tilde{c}))^N)F(x_0)(1-F(x_0))^{N-1} \\ \geq& 0.\end{aligned}$$

Thus, $c = c^m_{min}(x_0), \Delta W$ has its minimum zero when $x_0 = \mathbb{E}[X] + c$ and its maximum at $x_0 = \bar{x}$.

In sum, ΔW is always nonnegative, has its minimum at $c = c^v_{min}(x_0)$, increases in x_0 and c monotonously, and has its maximum at $c = c^m_{min}(\bar{x})$ and $x_0 = \bar{x}$.

A.4.5 Area 5 with $r = x_0 > \mathbb{E}[X] + c$ and $c \in [c^m_{\text{min}}(r), \bar{x} - \mathbb{E}[X])$

In the mandatory setting, E^r_1 yields the expected welfare

$$W^m = \sum_{n=1}^{N} P_A(n,q) \int_{\underline{x}}^{x_0} F_{(1,n)}(t)dt - Nqc = \sum_{n=2}^{N} P_A(n,q) \int_{\underline{x}}^{x_0} F_{(2,n)}(t)dt,$$

where

$$c = P(0,q)\int_{\underline{x}}^{x_0} F(s)ds + \sum_{n=1}^{N-1} P(n,q) \int_{\underline{x}}^{x_0} F(t)(1-F_{(1,n)}(t))dt.$$

In the voluntary setting, E_{mix} with $q_1 \in (0,1)$ and $q_2 = 1 - q_1$ yields the expected welfare

$$\begin{aligned}W^v =& P_A(N,q_1)\int_{\underline{x}}^{x_0} F_{(1,N)}(t)dt + \sum_{n_1=1}^{N-1} P_A(n_1,q_1)\int_{\underline{x}}^{\mathbb{E}[X]+c} F_{(1,n_1)}(t)dt \\ &+ (1-P_A(N,q_1))(x_0 - \mathbb{E}[X] - c) - Nq_1c,\end{aligned}$$

where

$$c = \sum_{n_1=0}^{N-1} P(n_1,q_1)\int_{\underline{x}}^{\mathbb{E}[X]+c} F(t)(1-F(t))^{n_1}dt - P(N-1,q_1)\int_{\mathbb{E}[X]+c}^{r} (1-F(t))^N dt,$$

and

$$
\begin{aligned}
&Nq_1c \\
=&\sum_{n_1=0}^{N-1} Nq_1P(n_1,q_1)\int_{\underline{x}}^{\mathbb{E}[X]+c} F(t)(1-F(t))^{n_1}dt - Nq_1P(N-1,q_1)\int_{\mathbb{E}[X]+c}^{r}(1-F(t))^N dt \\
=&\sum_{n=1}^{N} P_A(n,q_1)\int_{\underline{x}}^{\mathbb{E}[X]+c} nF(t)(1-F(t))^{n-1}dt - P_A(N,q_1)\int_{\mathbb{E}[X]+c}^{x_0} N(1-F(t))^N dt.
\end{aligned}
$$

The welfare difference is

$$
\begin{aligned}
&\Delta W = W^v - W^m \\
=\ & P_A(N,q_1)\int_{\underline{x}}^{x_0} F_{(1,N)}(t)dt + \sum_{n_1=1}^{N-1} P_A(n_1,q_1)\int_{\underline{x}}^{\mathbb{E}[X]+c} F_{(1,n_1)}(t)dt \\
&+ (1-P_A(N,q_1))(x_0-\mathbb{E}[X]-c) - \sum_{n=2}^{N} P_A(n,q)\int_{\underline{x}}^{x_0} F_{(2,n)}(t)dt \\
&- \sum_{n=1}^{N} P_A(n,q_1)\int_{\underline{x}}^{\mathbb{E}[X]+c} nF(t)(1-F(t))^{n-1}dt + P_A(N,q_1)\int_{\mathbb{E}[X]+c}^{x_0} N(1-F(t))^N dt \\
=\ & P_A(N,q_1)\int_{\underline{x}}^{x_0} F_{(1,N)}(t)dt - P_A(N,q_1)\int_{\underline{x}}^{\mathbb{E}[X]+c} F_{(1,N)}(t)dt \\
&+ \sum_{n_1=2}^{N} P_A(n_1,q_1)\int_{\underline{x}}^{\mathbb{E}[X]+c} F_{(2,n_1)}(t)dt + (1-P_A(N,q_1))(x_0-\mathbb{E}[X]-c) \\
&- \sum_{n=2}^{N} P_A(n,q)\int_{\underline{x}}^{x_0} F_{(2,n)}(t)dt + P_A(N,q_1)\int_{\mathbb{E}[X]+c}^{x_0} N(1-F(t))^N dt \\
=\ & P_A(N,q_1)\int_{\mathbb{E}[X]+c}^{x_0} (N-1)(1-F(t))^N dt + \sum_{n_1=2}^{N} P_A(n_1,q_1)\int_{\underline{x}}^{\mathbb{E}[X]+c} F_{(2,n_1)}(t)dt \\
&+ (x_0-\mathbb{E}[X]-c) - \sum_{n=2}^{N} P_A(n,q)\int_{\underline{x}}^{x_0} F_{(2,n)}(t)dt.
\end{aligned}
$$

If $x_0 \geq \bar{x}$

$$\begin{aligned}
&\Delta W \\
&= P_A(N, q_1) \int_{\mathbb{E}[X]+c}^{\bar{x}} (N-1)(1-F(t))^N dt + \sum_{n=2}^{N} P_A(n, q_1) \int_{\underline{x}}^{\mathbb{E}[X]+c} F_{(2,n)}(t) dt \\
&\quad + (\bar{x} - \mathbb{E}[X] - c) - \sum_{n=2}^{N} P_A(n, q) \int_{\underline{x}}^{\bar{x}} F_{(2,n)}(t) dt + (P_A(0, q) + P_A(1, q))(x_0 - \bar{x}) \\
&\geq P_A(N, q_1) \int_{\mathbb{E}[X]+c}^{\bar{x}} (N-1)(1-F(t))^N dt + \sum_{n=2}^{N} P_A(n, q_1) \int_{\underline{x}}^{\mathbb{E}[X]+c} F_{(2,n)}(t) dt \\
&\quad + (\bar{x} - \mathbb{E}[X] - c) - \sum_{n=2}^{N} P_A(n, q) \int_{\underline{x}}^{\bar{x}} F_{(2,n)}(t) dt \\
&:= \underline{\Delta W},
\end{aligned}$$

$$\begin{aligned}
\frac{\partial \underline{\Delta W}}{\partial c} = & - P_A(N, q_1)(N-1)(1-F(\mathbb{E}[X]+c))^N + \sum_{n=2}^{N} P_A(n, q_1) F_{(2,n)}(\mathbb{E}[X]+c) - 1 \\
\leq & - P_A(N, q_1)(N-1)(1-F(\mathbb{E}[X]+c))^N + 1 - P_A(0, q_1) - P_A(1, q_1) - 1 \\
\leq & \; 0.
\end{aligned}$$

Thus, $\underline{\Delta W}$ has its minimum when $c = \bar{x} - \mathbb{E}[X]$. Since $q_1 = q = 0$ at $c = \bar{x} - \mathbb{E}[X]$, we have $\underline{\Delta W} = \bar{x} - \mathbb{E}[X] - c = 0$. Therefore, $\Delta W \geq \underline{\Delta W} = 0$, and hence the expected welfare in the voluntary setting is always larger than or equal to that in the mandatory setting.

If $x_0 < \bar{x}$,

$$\begin{aligned}
\Delta W = & P_A(N, q_1) \int_{\mathbb{E}[X]+c}^{x_0} (N-1)(1-F(t))^N dt + \sum_{n_1=2}^{N} P_A(n_1, q_1) \int_{\underline{x}}^{\mathbb{E}[X]+c} F_{(2,n_1)}(t) dt \\
& + (x_0 - \mathbb{E}[X] - c) - \sum_{n=2}^{N} P_A(n, q) \int_{\underline{x}}^{x_0} F_{(2,n)}(t) dt \\
> & P_A(N, q_1) \int_{\mathbb{E}[X]+c}^{x_0} (N-1)(1-F(t))^N dt + \sum_{n_1=2}^{N} P_A(n_1, q_1) \int_{\underline{x}}^{\mathbb{E}[X]+c} F_{(2,n_1)}(t) dt \\
& + (x_0 - \mathbb{E}[X] - c) - \int_{\underline{x}}^{x_0} F_{(1,N)}(t) dt + Nc \\
:= & \Delta W'.
\end{aligned}$$

Analogous to the proof of Lemma 2, since $F_{(2,n_1)}$ increases in n_1, $P_A(n_1, q_1)$ increases in q if $q \in [0, \frac{n}{N})$ and decreases in q if $q \in (\frac{n}{N}, 1]$, it can be shown that $\sum_{n=2}^{N} P_A(n, q) \int_{\underline{x}}^{x_0} F_{(2,n)}(t) dt$ increases in q. Thus, the maximum is at $q = 1$, which is $\int_{\underline{x}}^{x_0} F_{(1,N)}(t) dt - Nc$. In Area 5 with

$x_0 < \bar{x}$, $q \in (0,1)$, therefore $\Delta W > \Delta W'$.

Note that $\Delta W'$ corresponds to ΔW in Area 4. To find the minimum of $\Delta W'$, the same minimizing problem as in Section A.4.4 should be solved. As shown above, the minimizing problem has the following KKT points: $q_1 = 1, \lambda = N, \mu_1 = 0$, $c = c^v_{min}(x_0)$, μ_2 depends on x_0 according to Constraint (A.13) and x_0 arbitrary. However, these points are not in Area 5. Thus, there exists no internal minimum or maximum. Next, we compare all ΔW on the boundary: If $x_0 = \bar{x}$, as mentions above, $\Delta W = \Delta W' \geq 0$ and $\Delta W'$ decreases in c; if $x_0 = \int_{\underline{x}}^{x_0} F(t)(1-F(t))^{N-1}dt, \Delta W = \Delta W' = 0$; if $q_1 = 1$, $\Delta W = \Delta W' = 0$; if $q_1 = 0$, $\Delta W = 0$ (see Section A.4.7); if $c = c^m_{min}(x_0) := \tilde{c}$, $\Delta W = \Delta W' \geq 0$ and $\Delta W'$ increases in x_0 (see Section A.4.4); if $c = \bar{x} - \mathbb{E}[X]$, $\Delta W = 0$ (see Section A.4.7).

In sum, ΔW is always nonnegative, has its minimum at $x_0 = \mathbb{E}[X] + c$, increases in x_0 and decreases in c monotonously, and has its maximum at $c = c^m_{min}(\bar{x})$ and $x_0 = \bar{x}$.

A.4.6 Area 6 with $r = x_0 > \mathbb{E}[X] + c > \bar{x}$ and $c \in [\bar{x} - \mathbb{E}[X], x_0 - \mathbb{E}[X])$

In the mandatory setting, E_1^r yields the expected welfare

$$\begin{aligned} W^m &= \sum_{n=1}^{N} P_A(n,q) \left[\int_{\underline{x}}^{\bar{x}} (x_0 - t) f_{(1,n)}(t) dt - n \cdot c \right] \\ &= \sum_{n=1}^{N} P_A(n,q) \left[\int_{\underline{x}}^{\bar{x}} (x_0 - t) f_{(1,n)}(t) dt \right] - Nqc \\ &= \sum_{n=2}^{N} P_A(n,q) \int_{\underline{x}}^{x_0} F_{(2,n)}(t) dt, \end{aligned}$$

where

$$c = P(0,q) \int_{\underline{x}}^{x_0} F(s) ds + \sum_{n=1}^{N-1} P(n,q) \int_{\underline{x}}^{\bar{x}} F(t)(1 - F_{(1,n)}(t)) dt.$$

In the voluntary setting, E_2 yields the expected welfare

$$W^v = x_0 - \mathbb{E}[X] - c > 0. \tag{A.14}$$

The welfare difference is

$$\begin{aligned}\Delta W =& W^v - W^m \\ =& x_0 - \mathbb{E}[X] - c - \sum_{n=2}^{N} P_A(n,q) \int_{\underline{x}}^{x_0} F_{(2,n)}(t)dt \\ =& x_0 - \mathbb{E}[X] - \sum_{n=2}^{N} P_A(n,q) \int_{\underline{x}}^{x_0} F_{(2,n)}(t)dt - P(0,q) \int_{\underline{x}}^{x_0} F(s)ds \\ &- \sum_{n=1}^{N-1} P(n,q) \int_{\underline{x}}^{\bar{x}} F(t)(1 - F_{(1,n)}(t))dt.\end{aligned}$$

It holds that

$$\frac{\partial \Delta W}{\partial x_0} = P_A(0,q) + P_A(1,q) - P(0,q) = (N-1)q(1-q)^{N-1} \geq 0.$$

Thus, ΔW has its minimum at $x_0 = \mathbb{E}[X] + c$, where $q = 0$ and $\Delta W = 0$. As a result, $\Delta W \geq 0$ and the expected welfare in the voluntary setting is always larger than or equal to that in the mandatory setting.

A.4.7 Area 7 with $r = x_0 = \mathbb{E}[X] + c$ and $c \geq \bar{x} - \mathbb{E}[X]$

In the mandatory setting, no equilibrium exists and thus $W^m = 0$. In the voluntary setting, E_2 yields the expected welfare

$$W^v = x_0 - \mathbb{E}[X] - c = 0 = W^m.$$

So the expected welfare is always the same in mandatory and voluntary settings.

□

A.5 Comparison under optimal reserve price

Locally optimal reserve price In E_{mix}, the coexistence of investors and non-investors induces a contracted distribution function F' of the (expected) private cost, where $F' \succ_{\text{SSD}} F$ and $F' = q_1 F + (1 - q_1)\delta_{\mathbb{E}[X]+c}$, with $\delta_{\mathbb{E}[X]+c}$ denoting a point mass at $\mathbb{E}[X] + c$. For any $r > \mathbb{E}[X] + c$, $F'(r) = q_1 F(r) + (1 - q_1)$, $f'(r) = q_1 f(r)$, which implies

$$\frac{F'(r)}{f'(r)} = \frac{q_1 F(r) + (1-q_1)}{q_1 f(r)} = \frac{F(r)}{f(r)} + \frac{1-q_1}{q_1 f(r)} \geq \frac{F(r)}{f(r)}.$$

The equality holds if and only if $q_1 = 1$. Let $\gamma_v(r) := \gamma_{F'}(r)$, which is increasing in r. Then $\gamma_v(r) \geq \gamma_F(r) = \gamma_m(r)$. According to Myerson (1981), $r^* = \gamma^{-1}(x_0)$, and therefore in E_{mix},

$r^* = \gamma_v^{-1}(x_0) \leq \gamma_m^{-1}(x_0)$, where $\gamma_m^{-1}(x_0)$ is the optimal reserve price in E^f. Consequently, $r^* \leq x_0 - \frac{F(r^*)}{f(r^*)}$.

Proof of Proposition 6. From the optimal reserve price we learn that $(r = x_0, c)$ and (r^*, c) always belong to the same equilibrium (including the boundary). In area 1,3,6,7, the participants expect a zero profit in both settings.In Area 2, $r_m^*(x_0) = r_v^*(x_0)$, participants expect the same profit which is strictly positive if

$$r_m^*(x_0) = r_v^*(x_0) > \{x \mid c_{min}^m(x) = c\} := L_2(c) \Rightarrow x_0 > \gamma_m(L_2(c)).$$

Under uniform distribution, this means that $x_0 > 2L_2(c)$. In area 5, $\mathbb{E}[\pi_i^{vn}] = \mathbb{E}[\pi_i^{vi}] - c \geq \mathbb{E}[\pi_i^m] - c = 0$, where the difference is strictly positive if

$$r_v^*(x_0) > \mathbb{E}[X] + c \Rightarrow x_0 > \gamma_v(\mathbb{E}[X] + c).$$

In area 4, however, participants can expect higher profits in the mandatory setting: $\mathbb{E}[\pi_i^m] - c > \mathbb{E}[\pi_i^{vn}] = \mathbb{E}[\pi_i^{vi}] - c = 0$ if $r_m^*(x_0) > L_2(c) = r_v^*(x_0) \Rightarrow \gamma_m(\mathbb{E}[X] + c) < x_0 \leq \gamma_v(\mathbb{E}[X] + c)$.

□

Proof of Proposition 7. For the auctioneer: We only consider the relevant cases where equilibrium exists in both settings, namely when $x_0 > L_1(c)$, where $L_1(c) := \{x \mid c_{max}(x) = \int_{\underline{x}}^{x} F(s)ds = c\}$. In the special case $x_0 = \mathbb{E}[X] + c$ and $c \geq \bar{x} - \mathbb{E}[X]$, where an equilibrium only exists in the voluntary setting (E_2), $r^* = x_0$ and thus $\pi_0 = 0$ as in the mandatory setting where no equilibrium exists.

In case $c \geq \bar{x} - \mathbb{E}[X]$, we have $x_0 > L_1(c) \geq L_1(\bar{x} - \mathbb{E}[X]) = \bar{x}$.

$$r_m^*(x_0) = x_0.$$

$$r_v^*(x_0) \in [\bar{x}, x_0].$$

$$\pi_0^m = \sum_{n=2}^{N} P_A(n,q) \int_{\underline{x}}^{\bar{x}} (x_0 - t) f_{(2,n)}(t)dt = \sum_{n=2}^{N} P_A(n,q) \int_{\underline{x}}^{x_0} F_{(2,n)}(t)dt.$$

$$\pi_0^v = x_0 - \mathbb{E}[X] - c.$$

$$\Delta\pi_0 = \pi_0^v - \pi_0^m = x_0 - \mathbb{E}[X] - c - \sum_{n=2}^{N} P_A(n,q) \int_{\underline{x}}^{x_0} F_{(2,n)}(t)dt.$$

which is equal to ΔW in Area 6 (see Section A.4.6) and thus

$$\frac{\partial \Delta\pi_0}{\partial x_0} = \frac{\partial \Delta W}{\partial x_0} = P_A(0,q) + P_A(1,q) - P(0,q) \geq 0.$$

Therefore, given a c, $\Delta\pi_0$ has its minimum at $x_0 = \mathbb{E}[X] + c$, where $q = 0$ and thus $\pi_0^m = \pi_0^v = 0$. As a result, $\pi_0^v \geq \pi_0^m$.

In case $c_{min}^m(\bar{x}) \leq c < \bar{x} - \mathbb{E}[X]$, the optimal reserve prices are given by

$$r_m^*(x_0) = x_0,$$

$$r_v^*(x_0) = \begin{cases} x_0, \text{ if } x_0 \leq \mathbb{E}[X] + c, \\ \mathbb{E}[X] + c, \text{ if } \mathbb{E}[X] + c < x_0 \leq \gamma_v(\mathbb{E}[X] + c), \\ (\gamma_v)^{-1}(x_0), \text{ if } \gamma_v(\mathbb{E}[X] + c) < x_0 \leq \gamma_v(\bar{x}), \\ r_v^*(x_0) \in [\bar{x}, x_0], \text{ if } x_0 > \gamma_v(\bar{x}). \end{cases}$$

For $x_0 \leq \mathbb{E}[X] + c$, both settings yield the same optimal reserve price and the same equilibrium. In the following, we focus on the case when $x_0 > \mathbb{E}[X] + c$ and assume that if $r_v = \mathbb{E}[X] + c$, $q_2 = 1 - q_1$. The expected profit of the auctioneer in the mandatory setting is

$$\pi_0^m = \sum_{n=2}^{N} P_A(n,q) \int_{\underline{x}}^{x_0} F_{(2,n)}(t)dt = \sum_{n=1}^{N} P_A(n,q) \int_{\underline{x}}^{x_0} F_{(1,n)}(t)dt - Nqc,$$

where $c = \sum_{n=0}^{N-1} P(n,q) \int_{\underline{x}}^{x_0} F(t)(1-F(t))^n dt$.

For a given reserve price r_v, the expected profit of the auctioneer in the voluntary setting is denoted $\pi_0^v(r_v)$. We first consider $r_v^1 = \mathbb{E}[X] + c$:

$$\begin{aligned}
&\pi_0^v(r_v^1) \\
=&(P_A(0,q_1) + P_A(1,q_1))(x_0 - \mathbb{E}[X] - c) \\
&+ \sum_{n=2}^{N-1} P_A(n,q_1) \left[\int_{\underline{x}}^{\mathbb{E}[X]+c} (x_0 - t) f_{(2,n)}(t)dt + (1 - F_{(2,n)}(\mathbb{E}[X]+c))(x_0 - \mathbb{E}[X] - c) \right] \\
&+ P_A(N,q_1) \left[\int_{\underline{x}}^{\mathbb{E}[X]+c} (x_0 - t) f_{(2,N)}(t)dt + (F_{(1,N)}(\mathbb{E}[X]+c) - F_{(2,N)}(\mathbb{E}[X]+c))(x_0 - \mathbb{E}[X] - c) \right] \\
=&\big[1 - P_A(N,q_1)(1 - F_{(1,N)}(\mathbb{E}[X]+c))\big](x_0 - \mathbb{E}[X] - c) + \sum_{n=2}^{N} P_A(n,q_1) \int_{\underline{x}}^{\mathbb{E}[X]+c} F_{(2,n)}(t)dt,
\end{aligned}$$

where $c = \sum_{n_1=0}^{N-1} P(n_1, q_1) \int_{\underline{x}}^{\mathbb{E}[X]+c} F(t)(1-F(t))^{n_1} dt$; similarly, for $r_v^2 = x_0$:

$$\begin{aligned}
\pi_0^v(r_v^2) =&(P_A(0,q_1) + P_A(1,q_1))(x_0 - \mathbb{E}[X] - c) \\
&+ \sum_{n_1=2}^{N-2} P_A(n_1, q_1) \left[(1 - F_{(2,n_1)}(\mathbb{E}[X]+c))(x_0 - \mathbb{E}[X] - c) + \int_{\underline{x}}^{\mathbb{E}[X]+c} (x_0 - t) f_{(2,n_1)}(t) dt \right] \\
&+ P_A(N-1, q_1) \left[\int_{\mathbb{E}[X]+c}^{x_0} (x_0 - t) f_{(1,N-1)}(t) dt + \right. \\
&\left. (F_{(1,N-1)}(\mathbb{E}[X]+c) - F_{(2,N-1)}(\mathbb{E}[X]+c))(x_0 - \mathbb{E}[X] - c) + \int_{\underline{x}}^{\mathbb{E}[X]+c} (x_0 - t) f_{(2,N-1)}(t) dt \right] \\
&+ P_A(N, q_1) \left[\int_{\underline{x}}^{x_0} (x_0 - t) f_{(2,N)}(t) dt \right] \\
=&(1 - P_A(N-1, q_1) - P_A(N, q_1))(x_0 - \mathbb{E}[X] - c) + \sum_{n_1=2}^{N} P_A(n_1, q_1) \int_{\underline{x}}^{\mathbb{E}[X]+c} F_{(2,n_1)}(t) dt \\
&+ P_A(N-1, q_1) \int_{\mathbb{E}[X]+c}^{x_0} F_{(1,N-1)}(t) dt + P_A(N, q_1) \int_{\mathbb{E}[X]+c}^{x_0} F_{(2,N)}(t) dt \\
=&(x_0 - \mathbb{E}[X] - c) + \sum_{n_1=2}^{N} P_A(n_1, q_1) \int_{\underline{x}}^{\mathbb{E}[X]+c} F_{(2,n_1)}(t) dt - P_A(N-1, q_1) \int_{\mathbb{E}[X]+c}^{x_0} (1 - F(t))^{N-1} dt \\
&- P_A(N, q_1) \int_{\mathbb{E}[X]+c}^{x_0} (1 - F(t))^N + N F(t)(1 - F(t))^{N-1} dt,
\end{aligned}$$

where $c = \sum_{n_1=0}^{N-1} P(n_1, q_1) \int_{\underline{x}}^{\mathbb{E}[X]+c} F(t)(1-F(t))^{n_1} dt - P(N-1, q_1) \int_{\mathbb{E}[X]+c}^{x_0} (1-F(t))^N dt$.

To compare $\pi_0^v(r_v^1)$ with $\pi_0^v(r_v^2)$, consider the two extreme cases of c.

If $c \to \bar{x} - \mathbb{E}[X]$, $q_1 \to 0$ under both reserve prices, so $\pi_0^v(r_v^1) \to x_0 - \mathbb{E}[X] - c$, and $\pi_0^v(r_v^2) \to x_0 - \mathbb{E}[X] - c$. That is, only non-investors with bids $\mathbb{E}[X] + c$ participate. Thus, the optimal reserve price $r_v^*(x_0)$ remains at the level of $\mathbb{E}[X] + c$ and $\gamma_v(\mathbb{E}[X] + c) \to \infty$.

If $c \to c_{min}^m(\bar{x})$, the difference in q_1 between r_v^1 and r_v^2 increases in x_0 and has its maximum at $x_0 \geq \bar{x}$. For $x_0 \geq \bar{x}$, a $r_v^2 \geq \bar{x}$ never sets the price and thus has the same effect on q_1 as $r_v = \bar{x}$. Consider the case $x_0 \geq \bar{x}$ and let $r_v = \bar{x}$ without loss of generality. Then we have

$$\begin{aligned}
&\pi_0^v(r_v^2 \geq \bar{x}) = \pi_0^v(r_v = \bar{x}) \\
=&(x_0 - \mathbb{E}[X] - c) + \sum_{n_1 \in [2,N]} P_A(n_1, q_1) \int_{\underline{x}}^{\mathbb{E}[X]+c} F_{(2,n_1)}(t) dt \\
&- P_A(N-1, q_1) \int_{\mathbb{E}[X]+c}^{\bar{x}} (1 - F(t))^{N-1} dt - P_A(N, q_1) \int_{\mathbb{E}[X]+c}^{\bar{x}} (1 - F(t))^{N-1}(1 + (N-1)F(t)) dt.
\end{aligned}$$

Since $\frac{d\pi_0^v(\mathbb{E}[X]+c)}{dx_0} = 1 - P_A(N, q_1)(1 - F_{(1,N)}(\mathbb{E}[X] + c)) < 1 = \frac{d\pi_0^v(x_0)}{dx_0}$, $\pi_0^v(r_v^2)$ increases more than $\pi_0^v(r_v^1)$ as x_0 increases. As a result, $\pi_0^v(r_v^2)$ surpasses $\pi_0^v(r_v^1)$ for sufficiently large x_0, making the optimal reserve price increase beyond $r_v^1 = \mathbb{E}[X] + c$. This is consistent with the

$r_v^*(x_0)$, where the reserve price increases after x_0 reaches a $\gamma_v(\mathbb{E}[X]+c)$.

Comparing the equilibrium conditions

$$c = \sum_{n_1=0}^{N-1} P(n_1, q_1) \int_{\underline{x}}^{\mathbb{E}[X]+c} F(t)(1-F(t))^{n_1} dt$$

under r_v^1 and

$$c = \sum_{n_1=0}^{N-1} P(n_1, q_1) \int_{\underline{x}}^{\mathbb{E}[X]+c} F(t)(1-F(t))^{n_1} dt - P(N-1, q_1) \int_{\mathbb{E}[X]+c}^{x_0} (1-F(t))^N dt$$

under r_v^2, we observe that the term $P(N-1, q_1) \int_{\mathbb{E}[X]+c}^{x_0} (1-F(t))^N dt$ decreases in c and converges to 0 as $c \to \bar{x} - \mathbb{E}[X]$, making the corresponding values of q_1 identical in both settings. For smaller c, this term becomes larger, resulting in a greater difference in q_1 between r_v^1 and r_v^2. This implies a larger relative advantage of r_v^2 over r_v^1. Consequently, when c is large and x_0 is (relatively) small, the optimal reserve price remains $\mathbb{E}[X]+c$, while for small c and (relatively) large x_0, the optimal reserve price rises from $\mathbb{E}[X]+c$ to $\bar{x}$.

After characterizing $r_v^*(x_0)$, we compare the profit difference $\Delta\pi_0 = \pi_0^v - \pi_0^m$.

Consider first the case where $c \to \bar{x} - \mathbb{E}[X]$ and $x_0 < \infty$, then $r_v^*(x_0) = \mathbb{E}[X]+c$,

$$\begin{aligned}
&\Delta\pi_0 = \pi_0^v(\mathbb{E}[X]+c) - \pi_0^m \\
=&(1-P_A(N, q_1)(1-F_{(1,N)}(\mathbb{E}[X]+c))(x_0 - \mathbb{E}[X] - c) + \sum_{n=2}^{N} P_A(n, q_1) \int_{\underline{x}}^{\mathbb{E}[X]+c} F_{(2,n)}(t) dt \\
&- \sum_{n=2}^{N} P_A(n, q) \int_{\underline{x}}^{x_0} F_{(2,n)}(t) dt,
\end{aligned}$$

where $q_1 \to 0$, $q \to 0$ and thus $\Delta\pi_0 \to x_0 - \mathbb{E}[X] - c > 0$.

Consider then the following specific case: Suppose $X_i, i \in \{1, ..., N\}$ are uniform distributed on the interval $[\underline{x}, \bar{x}] = [0, 1]$, $c = c_{min}^m(\bar{x}) = \frac{1}{N(N+1)}$, and $x_0 \in [\bar{x}, \gamma_v(\mathbb{E}[X]+c)]$ We have $r_m^*(x_0) = x_0$ and

$$\gamma_v(\mathbb{E}[X]+c) \geq \gamma_m(\mathbb{E}[X]+c) = \mathbb{E}[X]+c+\frac{F(\mathbb{E}[X]+c)}{f(\mathbb{E}[X]+c)} = 2(\mathbb{E}[X]+c) = 1 + \frac{2}{N(N+1)} > \bar{x},$$

implying $r_v^*(x_0) = \mathbb{E}[X]+c = \frac{1}{2} + \frac{1}{N(N+1)}$. Under $r_m^*(x_0) = x_0 > \bar{x}$, $q = 1$ and $\pi_0^m = \frac{N-1}{N+1} + (x_0 - 1)$. Under $r_v^*(x_0) = \frac{1}{2} + \frac{1}{N(N+1)}$, q_1 is determined by

$$c = \sum_{n_1=0}^{N-1} P(n_1, q_1) \int_{\underline{x}}^{\mathbb{E}[X]+c} F(t)(1-F(t))^{n_1} dt$$
$$\Leftrightarrow c = \sum_{n_1=0}^{N-1} P(n_1, q_1) \left[-\frac{(\mathbb{E}[X]+c)(1-\mathbb{E}[X]-c)^{n+1})}{n+1} - \frac{(1-\mathbb{E}[X]-c)^{n+2}}{(n+1)(n+2)} + \frac{1}{(n+1)(n+2)} \right]$$
$$\Leftrightarrow c = -\frac{(\mathbb{E}[X]+c)(1-q_1(\mathbb{E}[X]+c))^N}{Nq_1} + \frac{(\mathbb{E}[X]+c)(1-q_1)^N}{Nq_1}$$
$$- \frac{(1-q_1(\mathbb{E}[X]+c))^{N+1}}{N(N+1)q_1^2} + \frac{(1-q_1)^{N+1}}{N(N+1)q_1^2} + \frac{(N+1)q_1(1-\mathbb{E}[X]-c)(1-q_1)^N}{N(N+1)q_1^2}$$
$$+ \frac{1-(1-q_1)^{N+1}-(N+1)q_1(1-q_1)^N}{N(N+1)q_1^2}$$
$$\Leftrightarrow \frac{1}{N(N+1)} = \frac{1-(1-q_1(\frac{1}{2}+\frac{1}{N(N+1)}))^{N+1}}{N(N+1)q_1^2} - \frac{(\frac{1}{2}+\frac{1}{N(N+1)})(1-q_1(\frac{1}{2}+\frac{1}{N(N+1)}))^N}{Nq_1}$$
$$\Rightarrow 1 - q_1^2 - (1-(\frac{1}{2}+\frac{1}{N(N+1)})q_1)^N(1+N(\frac{1}{2}+\frac{1}{N(N+1)})q_1) = 0.$$

$$\pi_0^v = \left[1 - P_A(N,q_1)(1-F_{(1,N)}(\mathbb{E}[X]+c))\right](x_0 - \mathbb{E}[X] - c) + \sum_{n=2}^{N} P_A(n,q_1) \int_{\underline{x}}^{\mathbb{E}[X]+c} F_{(2,n)}(t)dt$$
$$= \left[1 - q_1^N(1-F(\mathbb{E}[X]+c))^N\right](x_0 - \mathbb{E}[X] - c)$$
$$+ \sum_{n=2}^{N} P_A(n,q_1) \left[\mathbb{E}[X] + c + (\mathbb{E}[X]+c)(1-\mathbb{E}[X]-c)^N - \frac{2}{N+1} + \frac{2(1-\mathbb{E}[X]-c)^{N+1}}{N+1} \right]$$
$$= \left[1 - q_1^N(1-F(\mathbb{E}[X]+c))^N\right](x_0 - \mathbb{E}[X] - c) + \mathbb{E}[X] + c + (\mathbb{E}[X]+c)(1-q_1(\mathbb{E}[X]+c))^N$$
$$- \frac{2-2(1-q_1)^{N+1}}{(N+1)q_1} + \frac{2(1-q_1(\mathbb{E}[X]+c))^{N+1} - 2(1-q)^{N+1}}{(N+1)q_1}$$
$$= 1 - q_1^N(\frac{1}{2} - \frac{1}{N(N+1)})^{N+1} + (\frac{1}{2}+\frac{1}{N(N+1)})(1-(\frac{1}{2}+\frac{1}{N(N+1)})q_1)^N$$
$$+ \frac{2}{q_1(N+1)}[(1-(\frac{1}{2}+\frac{1}{N(N+1)})q_1)^{N+1} - 1] + (x_0 - 1)(1 - q_1^N(\frac{1}{2} - \frac{1}{N(N+1)})^N).$$

With different N, the numerical values of π_0^m and π_0^v are calculated in the following table.

Table A.1: Examples of numeric values of π_0^m and π_0^v under uniform distribution

N	c	π_0^m	q_1	π_0^v	$\Delta\pi_0$
3	$\frac{1}{12}$	$0.5+(x_0-1)$	0.7938	$0.4977+0.9638(x_0-1)$	$-0.0023-0.0362(x_0-1)$
4	$\frac{1}{20}$	$0.6+x_0-1$	0.8965	$0.5932+0.9735(x_0-1)$	$-0.0068-0.0265(x_0-1)$
5	$\frac{1}{30}$	$0.67+(x_0-1)$	0.9459	$0.6609+0.9832(x_0-1)$	$-0.0057-0.0168(x_0-1)$

As shown in Table A.1, $\Delta\pi_0 < 0$ at $x_0 \in [\bar{x}, \gamma_v(\mathbb{E}[X]+c)]$ and $c = c^m_{min}(\bar{x})$.

Overall, we find both examples with $\Delta\pi_0 > 0$ and $\Delta\pi_0 < 0$. Particularly with high c, the expected profit of auctioneer favors the voluntary setting.

□

Appendix B

Appendix to Chapter 3

B.1 Basic model

Proof of Lemma 6. For a risk-neutral bidder, the indifference price and the implementation decision only depend on the expected revenue. Thus, it holds that $b_C^* = b_N^* + \mathbb{E}[Z] - \tau$ and $y_C^*(b_C^*) = y_N^*(b_N^*)$. Given these two conditions, it is easy to prove that $U_C(b_C^*) = U_N(b_N^*)$ and $u(w + b_C^* - \theta - y_C^*(b_C^*)) = \int_{\underline{z}}^{\bar{z}} u(w + b_N^* - \theta - \tau - y_N^*(b_N^*) + z)h(z)dz$.

For a risk-averse bidder, first assume $b_C^* = b_N^* + \mathbb{E}[Z] - \tau$ and $y_C^*(b_C^*) = y_N^*(b_N^*)$, as in the risk-neutral case. According to (3.5), by setting $y_C^*(b_C^*) = y_N^*(b_N^*)$, we have

$$\int_{\underline{y}}^{y_C^*(b_C^*)} u(w + b_C^* - \theta - y)g(y)dy = \int_{\underline{y}}^{y_N^*(b_N^*)} \int_{\underline{z}}^{\bar{z}} u(w + b_N^* - \theta - \tau - y + z)h(z)dzg(y)dy. \quad (B.1)$$

Because of risk aversion and by setting $b_C^* = b_N^* + \mathbb{E}[Z] - \tau$, it holds that

$$\int_{\underline{y}}^{y_N^*(b_N^*)} \int_{\underline{z}}^{\bar{z}} u(w + b_N^* - \theta - \tau - y + z)h(z)dzg(y)dy \quad (B.2)$$

$$< \int_{\underline{y}}^{y_N^*(b_N^*)} u(w + b_N^* - \theta - \tau - y + \mathbb{E}[Z])g(y)dy \quad (B.3)$$

$$= \int_{\underline{y}}^{y_C^*(b_C^*)} u(w + b_C^* - \theta - y)g(y)dy.$$

This contradicts Equation (B.1). Therefore, the assumption $b_C^* = b_N^* + \mathbb{E}[Z] - \tau$ and $y_C^*(b_C^*) = y_N^*(b_N^*)$ cannot hold. To increase expression (B.2) so that $U_C(b_C^*) = U_N(b_N^*)$, b_N^* or $y_N^*(b_N^*)$ must increase. According to (3.7), b_N^* and $y_N^*(b_N^*)$ are positively correlated – an increase in one requires an increase in the other. Consequently, both must increase. It follows that $b_C^* < b_N^* + \mathbb{E}[Z] - \tau$ and $y_C^*(b_C^*) < y_N^*(b_N^*)$.

Similarly, assume $b_C^* = b_N^* + \mathbb{E}[Z] - \tau$ and $y_C^*(b_C^*) = y_N^*(b_N^*)$ for a risk-seeking bidder, the corresponding expression (B.2) should be larger than expression (B.3), leading to a contradiction with Equation (B.1). Therefore, to satisfy the condition $U_C(b_C^*) = U_N(b_N^*)$, it must hold that $b_C^* > b_N^* + \mathbb{E}[Z] - \tau$ and $y_C^*(b_C^*) > y_N^*(b_N^*)$. □

Proof of Lemma 7. Under scenario C, according to Equation (3.6), it holds that

$$\begin{aligned}
&u(w + b_{C,j}^* - \theta_j - y_{C,j}^*(b_{C,j}^*)) = u(w - s) = u(w + b_{C,i}^* - \theta_i - y_{C,i}^*(b_{C,i}^*)) \\
\Leftrightarrow\ & w + b_{C,j}^* - \theta_j - y_{C,j}^*(b_{C,j}^*) = w - s = w + b_{C,i}^* - \theta_i - y_{C,i}^*(b_{C,i}^*) \\
\Rightarrow\ & b_{C,j}^* - \theta_j = y_{C,j}^*(b_{C,j}^*) - s,\ b_{C,i}^* - \theta_i = y_{C,i}^*(b_{C,i}^*) - s.
\end{aligned} \tag{B.4}$$

According to Equation (3.5), we have

$$U_C(y_{C,j}^*(b_{C,j}^*), b_{C,j}^*) = U_C(y_{C,i}^*(b_{C,i}^*), b_{C,i}^*) = u(w). \tag{B.5}$$

If $b_{C,j}^* - \theta_j < b_{C,i}^* - \theta_i$, then according to (B.4), $y_{C,j}^*(b_{C,j}^*) < y_{C,i}^*(b_{C,i}^*)$. We have

$$\begin{aligned}
&U_C(y_{C,i}^*(b_{C,i}^*), b_{C,i}^*) \\
=&\int_{\underline{y}}^{y_{C,i}^*(b_{C,i}^*)} u(w + b_{C,i}^* - \theta_i - y)g(y)dy + \int_{y_{C,i}^*(b_{C,i}^*)}^{\bar{y}} u(w - s)g(y)dy \\
=&\int_{\underline{y}}^{y_{C,j}^*(b_{C,j}^*)} u(w + b_{C,i}^* - \theta_i - y)g(y)dy + \int_{y_{C,j}^*(b_{C,j}^*)}^{y_{C,i}^*(b_{C,i}^*)} u(w + b_{C,i}^* - \theta_i - y)g(y)dy \\
&+ \int_{y_{C,j}^*(b_{C,j}^*)}^{\bar{y}} u(w - s)g(y)dy - \int_{y_{C,j}^*(b_{C,j}^*)}^{y_{C,i}^*(b_{C,i}^*)} u(w - s)g(y)dy \\
>&\int_{\underline{y}}^{y_{C,j}^*(b_{C,j}^*)} u(w + b_{C,j}^* - \theta_j - y)g(y)dy + \int_{y_{C,j}^*(b_{C,j}^*)}^{y_{C,i}^*(b_{C,i}^*)} u(w + b_{C,i}^* - \theta_i - y_{C,i}^*(b_{C,i}^*))g(y)dy \\
&+ \int_{y_{C,j}^*(b_{C,j}^*)}^{\bar{y}} u(w - s)g(y)dy - \int_{y_{C,j}^*(b_{C,j}^*)}^{y_{C,i}^*(b_{C,i}^*)} u(w - s)g(y)dy \\
=&U_C(y_{C,j}^*(b_{C,j}^*), b_{C,j}^*) + \int_{y_{C,j}^*(b_{C,j}^*)}^{y_{C,i}^*(b_{C,i}^*)} (u(w + b_{C,i}^* - \theta_i - y_{C,i}^*(b_{C,i}^*)) - u(w - s))g(y)dy \\
=&U_C(y_{C,j}^*(b_{C,j}^*), b_{C,j}^*).
\end{aligned}$$

This contradicts Equation (B.5), thus, $b_{C,j}^* - \theta_j < b_{C,i}^* - \theta_i$ does not hold.

If $b^*_{C,j} - \theta_j > b^*_{C,i} - \theta_i$, then according to (B.4), $y^*_{C,j}(b^*_{C,j}) > y^*_{C,i}(b^*_{C,i})$. We have

$$
\begin{aligned}
& U_C(y^*_{C,j}(b^*_{C,j}), b^*_{C,j}) \\
=& \int_{\underline{y}}^{y^*_{C,j}(b^*_{C,j})} u(w + b^*_{C,j} - \theta_j - y)g(y)dy + \int_{y^*_{C,j}(b^*_{C,j})}^{\bar{y}} u(w-s)g(y)dy \\
=& \int_{\underline{y}}^{y^*_{C,i}(b^*_{C,i})} u(w + b^*_{C,j} - \theta_j - y)g(y)dy + \int_{y^*_{C,i}(b^*_{C,i})}^{y^*_{C,j}(b^*_{C,j})} u(w + b^*_{C,j} - \theta_j - y)g(y)dy \\
& + \int_{y^*_{C,i}(b^*_{C,i})}^{\bar{y}} u(w-s)g(y)dy - \int_{y^*_{C,i}(b^*_{C,i})}^{y^*_{C,j}(b^*_{C,j})} u(w-s)g(y)dy \\
>& \int_{\underline{y}}^{y^*_{C,i}(b^*_{C,i})} u(w + b^*_{C,i} - \theta_i - y)g(y)dy + \int_{y^*_{C,i}(b^*_{C,i})}^{y^*_{C,j}(b^*_{C,j})} u(w + b^*_{C,j} - \theta_j - y^*_{C,j}(b^*_{C,j}))g(y)dy \\
& + \int_{y^*_{C,i}(b^*_{C,i})}^{\bar{y}} u(w-s)g(y)dy - \int_{y^*_{C,i}(b^*_{C,i})}^{y^*_{C,j}(b^*_{C,j})} u(w-s)g(y)dy \\
=& U_C(y^*_{C,i}(b^*_{C,i}), b^*_{C,i}) + \int_{y^*_{C,i}(b^*_{C,i})}^{y^*_{C,j}(b^*_{C,j})} (u(w + b^*_{C,j} - \theta_j - y^*_{C,j}(b^*_{C,j})) - u(w-s))g(y)dy \\
=& U_C(y^*_{C,i}(b^*_{C,i}), b^*_{C,i}).
\end{aligned}
$$

This contradicts Equation (B.5), thus, $b^*_{C,j} - \theta_j > b^*_{C,i} - \theta_i$ does not hold.

If $b^*_{C,j} - \theta_j = b^*_{C,i} - \theta_i$, then according to (B.4), $y^*_{C,j}(b^*_{C,j}) = y^*_{C,i}(b^*_{C,i})$. We have

$$
\begin{aligned}
U_C(y^*_{C,j}(b^*_{C,j}), b^*_{C,j}) =& \int_{\underline{y}}^{y^*_{C,j}(b^*_{C,j})} u(w + b^*_{C,j} - \theta_j - y)g(y)dy + \int_{y^*_{C,j}(b^*_{C,j})}^{\bar{y}} u(w-s)g(y)dy \\
=& \int_{\underline{y}}^{y^*_{C,i}(b^*_{C,i})} u(w + b^*_{C,i} - \theta_i - y)g(y)dy + \int_{y^*_{C,i}(b^*_{C,i})}^{\bar{y}} u(w-s)g(y)dy \\
=& U_C(y^*_{C,i}(b^*_{C,i}), b^*_{C,i}).
\end{aligned}
$$

This coincides with Equation (B.5), thus, $b^*_{C,j} - \theta_j = b^*_{C,i} - \theta_i$ and $y^*_{C,j}(b^*_{C,j}) = y^*_{C,i}(b^*_{C,i})$.

Under scenario N, according to Equation (3.7), it holds that

$$
\begin{aligned}
& \int_{\underline{z}}^{\bar{z}} u(w + b^*_{N,j} - \theta_j - \tau_j - y^*_{N,j}(b^*_{N,j}) + z)h(z)dz = u(w-s) && \text{(B.6)} \\
& = \int_{\underline{z}}^{\bar{z}} u(w + b^*_{N,i} - \theta_i - \tau_i - y^*_{N,i}(b^*_{N,i}) + z)h(z)dz \\
\Rightarrow\ & b^*_{N,j} - \theta_j - \tau_j - y^*_{N,j}(b^*_{N,j}) = b^*_{N,i} - \theta_i - \tau_i - y^*_{N,i}(b^*_{N,i}). && \text{(B.7)}
\end{aligned}
$$

According to Equation (3.5), we have

$$
U_N(y^*_{N,j}(b^*_{N,j}), b^*_{N,j}) = U_C(y^*_{N,i}(b^*_{N,i}), b^*_{N,i}) = u(w). \tag{B.8}
$$

If $b^*_{N,j} - \theta_j - \tau_j < b^*_{N,i} - \theta_i - \tau_i$, then according to (B.7), $y^*_{N,j}(b^*_{N,j}) < y^*_{N,i}(b^*_{N,i})$. We have

$$\begin{aligned}
& U_N(y^*_{N,i}(b^*_{N,i}), b^*_{N,i}) \\
&= \int_{\underline{y}}^{y^*_{N,i}(b^*_{N,i})} \int_{\underline{z}}^{\bar{z}} u(w + b^*_{N,i} - \theta_i - \tau_i - y + z)h(z)dzg(y)dy + \int_{y^*_{N,i}(b^*_{N,i})}^{\bar{y}} u(w-s)g(y)dy \\
&= \int_{\underline{y}}^{y^*_{N,j}(b^*_{N,j})} \int_{\underline{z}}^{\bar{z}} u(w + b^*_{N,i} - \theta_i - \tau_i - y + z)h(z)dzg(y)dy + \int_{y^*_{N,j}(b^*_{N,j})}^{\bar{y}} u(w-s)g(y)dy \\
&\quad + \int_{y^*_{N,j}(b^*_{N,j})}^{y^*_{N,i}(b^*_{N,i})} \int_{\underline{z}}^{\bar{z}} u(w + b^*_{N,i} - \theta_i - \tau_i - y + z)h(z)dzg(y)dy - \int_{y^*_{N,j}(b^*_{N,j})}^{y^*_{N,i}(b^*_{N,i})} u(w-s)g(y)dy \\
&> U_N(y^*_{N,j}(b^*_{N,j}), b^*_{N,j}) + \int_{y^*_{N,j}(b^*_{N,j})}^{y^*_{N,i}(b^*_{N,i})} \int_{\underline{z}}^{\bar{z}} (u(w + b^*_{N,i} - \theta_i - \tau_i - y^*_{N,i}(b^*_{N,i}) + z)h(z)dz - u(w-s))g(y)dy \\
&= U_N(y^*_{N,j}(b^*_{N,j}), b^*_{N,j}).
\end{aligned}$$

This contradicts Equation (B.8), thus, $b^*_{N,j} - \theta_j - \tau_j < b^*_{N,i} - \theta_i - \tau_i$ does not hold.

Analogously, if $b^*_{N,j} - \theta_j - \tau_j > b^*_{N,i} - \theta_i - \tau_i$, then according to (B.7), $y^*_{N,j}(b^*_{N,j}) > y^*_{N,i}(b^*_{N,i})$. We have $U_N(y^*_{N,j}(b^*_{N,j}), b^*_{N,j}) > U_N(y^*_{N,i}(b^*_{N,i}), b^*_{N,i})$, which contradicts Equation (B.8). Thus, $b^*_{N,j} - \theta_j - \tau_j > b^*_{N,i} - \theta_i - \tau_i$ does not hold.

If $b^*_{N,j} - \theta_j - \tau_j = b^*_{N,i} - \theta_i - \tau_i$, then according to (B.7), $y^*_{N,j}(b^*_{N,j}) = y^*_{N,i}(b^*_{N,i})$. And we have $U_N(y^*_{N,j}(b^*_{N,j}), b^*_{N,j}) = U_N(y^*_{N,i}(b^*_{N,i}), b^*_{N,i})$, which coincides with Equation (B.8). Thus, $b^*_{N,j} - \theta_j - \tau_j = b^*_{N,i} - \theta_i - \tau_i$ and $y^*_{N,j}(b^*_{N,j}) = y^*_{N,i}(b^*_{N,i})$. □

Proof of Lemma 8. Under scenario C, according to the equations (3.3) and (3.6), we have

$$\begin{aligned}
& u(w + b^*_{C,j} - \theta_i - y^*_{C,i}(b^*_{C,j})) = u(w-s) = u(w + b^*_{C,i} - \theta_i - y^*_{C,i}(b^*_{C,i})) \\
\Rightarrow\ & y^*_{C,i}(b^*_{C,j}) = y^*_{C,i}(b^*_{C,i}) + b^*_{C,j} - b^*_{C,i} = y^*_{C,i}(b^*_{C,i}) + b^*_{C,j} - b^*_{C,i}.
\end{aligned}$$

Since $b^*_{C,j} - \theta_j = b^*_{C,i} - \theta_i$ proved by Lemma 7, it holds that $y^*_{C,i}(b^*_{C,j}) = y^*_{C,i}(b^*_{C,i}) + \theta_j - \theta_i$.

Under scenario N, according to the equations (3.4) and (3.7), we have

$$\begin{aligned}
& \int_{\underline{z}}^{\bar{z}} u(w + b^*_{N,j} - \theta_i - \tau_i - y^*_{N,i}(b^*_{N,j}) + z)h(z)dz \\
&= \int_{\underline{z}}^{\bar{z}} u(w + b^*_{N,i} - \theta_i - \tau_i - y^*_{N,i}(b^*_{N,i}) + z)h(z)dz,
\end{aligned}$$

$$\begin{aligned}
\Rightarrow y^*_{N,i}(b^*_{N,j}) &= y^*_{N,i}(b^*_{N,i}) + b^*_{N,j} - b^*_{N,i} \\
&= y^*_{N,i}(b^*_{N,i}) + \theta^N_j - \theta^N_i. \qquad \text{(Lemma 7)}
\end{aligned}$$

□

Proof of Lemma 9. Since $\mathcal{T}$ is independent of Θ and Θ has a log-concave density, it holds that $\Theta \leq_{disp} \Theta^N = \Theta + \mathcal{T}$ (Shaked and Shanthikumar, 2007, Theorem 3.B.7.).[1] Then $\mathbb{E}[\Theta_{(i)}] - \mathbb{E}[\Theta^N_{(i)}]$ is decreasing in i (Alzaid and Proschan, 1992, Theorem 2.6). Thus, $\mathbb{E}[\Theta^N_{(i)}] - \mathbb{E}[\Theta_{(i)}]$ is increasing in i and $\mathbb{E}[Y_{(2)}] - \mathbb{E}[Y_{(1)}] \geq \mathbb{E}[X_{(2)}] - \mathbb{E}[X_{(1)}]$. □

Proof of Proposition 8. Let p_C and p_N denote the respective prices again, and let the winning bidders in auctions C and N be indexed as $(C1)$ and $(N1)$ respectively. Lemma 9 implies that $\mathbb{E}[\Delta(\Theta^N)] \geq \mathbb{E}[\Delta\Theta]$ for any two order statistics. Then we have $\Delta(\theta^N) > \Delta\theta$ in expectations and thus

$$
\begin{aligned}
y^*_{N,(N1)}(p_N) &= y^*_{N,(N1)}(b^*_{N,(N1)}) + \Delta(\theta^N) && \text{(Lemma 8)}\\
&\underset{(=)}{>} y^*_{C,(N1)}(b^*_{C,(N1)}) + \Delta(\theta^N) && \text{(Lemma 6)}\\
&= y^*_{C,(C1)}(b^*_{C,(C1)}) + \Delta(\theta^N) && \text{(Lemma 7)}\\
&\geq y^*_{C,(C1)}(b^*_{C,(C1)}) + \Delta(\theta) && \text{(Lemma 9)}\\
&= y^*_{C,(C1)}(p_C).
\end{aligned}
$$

In the second line, $>$ holds for risk-averse bidders and $=$ holds for risk-neutral bidders. For risk-seeking bidders, $<$ holds in the second line, so the comparison is ambiguous.

□

Proof of Proposition 9. If the bidder has τ_ℓ, then $\mathbb{E}[\Delta(\Theta^N)] > \mathbb{E}[\Delta(\Theta)]$, implying $\mathbb{E}[P_C] - b^*_C < \mathbb{E}[P_N] - b^*_N$, where P_C and P_N are the random variable of the awarded prices on condition that either b^*_C or b^*_N wins. For risk-neutral bidders, this yields $U_C(\mathbb{E}[P_C]) < U_N(\mathbb{E}[P_N])$. Besides, bidders with τ_ℓ have a relative competitive advantage in N compared to C, resulting in a higher winning probability in N than in C, i.e., $1 - F_C(b^*_C) < 1 - F_N(b^*_N)$. As a results, it holds that $EU_C(b^*_C) < EU_N(b^*_N)$. In addition, analog to the proof of Proposition 8, $\mathbb{E}[P_C] - b^*_C < \mathbb{E}[P_N] - b^*_N$ yields $y^*_C(\mathbb{E}[P_C]) < y^*_N(\mathbb{E}[P_N]) \Leftrightarrow \mathbb{E}[y^*_C(P_C)] < \mathbb{E}[y^*_N(P_N)]$. To summarize, the realization probability, the winning probability, and the expected utility are higher in N than in C. Under Assumption 1, the same results hold for risk-averse bidders, while for risk-seeking bidders, the comparison for winning probability and expected utility still hold, but not necessarily for the realization probability.

[1] Random variable X is less dispersive than random variable X', denoted by $X \leq_{disp} X'$, if and only if

$$F_X^{-1}(\beta) - F_X^{-1}(\alpha) \leq F_{X'}^{-1}(\beta) - F_{X'}^{-1}(\alpha)$$

for $0 < \alpha < \beta < 1$, where F_X and $F_{X'}$ denote the distribution functions of X and X' (e.g., Alzaid and Proschan, 1992, Def. 1.2).

If the bidder has τ_h, then $\mathbb{E}[\Delta(\Theta^N)] < \mathbb{E}[\Delta(\Theta)]$, implying $\mathbb{E}[P_C]-b_C^* > \mathbb{E}[P_N]-b_N^*$. For risk-neutral bidders, we have $y_C^*(\mathbb{E}[P_C]) > y_N^*(\mathbb{E}[P_N]) \Leftrightarrow \mathbb{E}[y_C^*(P_C)] > \mathbb{E}[y_N^*(P_N)]$, $1-F_C(b_C^*) > 1-F_N(b_N^*)$, and $EU_C(b_C^*) > EU_N(b_N^*)$. Under Assumption 1, the same results hold for risk-seeking bidders; for risk-averse bidders, the comparisons for winning probability and expected utility hold, but not necessarily for realization probability. □

B.2 Model extensions

Proof of Proposition 10. The risk-neutral bidder's ex-ante expected utility at the indifference price is:

$$\begin{aligned} U_C^{RN}(b_C^{RN}) &= \int_{\underline{y}}^{y_C^{RN}(b_C^{RN})} u^{RN}(w+b_C^{RN}-\theta-y)g(y)dy + \int_{y_C^{RN}(b_C^{RN})}^{\bar{y}} u^{RN}(w-s)g(y)dy \\ &= \int_{\underline{y}}^{y_C^{RN}(b_C^{RN})} (w+b_C^{RN}-\theta-y)g(y)dy + \int_{y_C^{RN}(b_C^{RN})}^{\bar{y}} (w-s)g(y)dy = u^{RN}(w), \end{aligned}$$

where the implementation cost threshold is determined by

$$u^{RN}(w+b_C^{RN}-\theta-y_C^{RN}(b_C^{RN})) = u^{RN}(w-s) \Leftrightarrow \; y_C^{RN}(b_C^{RN}) = b_C^{RN}-\theta+s.$$

Thus, we have

$$\begin{aligned} &U_C^{RN}(b_C^{RN}) = \int_{\underline{y}}^{b_C^{RN}-\theta+s} (w+b_C^{RN}-\theta-y)g(y)dy + \int_{b_C^{RN}-\theta+s}^{\bar{y}} (w-s)g(y)dy = w \\ &\Rightarrow G(b_C^{RN}-\theta+s)(w+b_C^{RN}-\theta-\mathbb{E}[Y \mid \underline{y} \le y \le b_C^{RN}-\theta+s]) + (1-G(b_C^{RN}-\theta+s))(w-s) = w. \end{aligned}$$

For the risk-averse bidder, from Equation (3.6) we have $y_C^{RA}(b_C^{RA}) = b_C^{RA}-\theta+s$. Assume that $b_C^{RA} = b_C^{RN}$, then we have

$$\begin{aligned} &U_C(b_C^{RA}) \\ &= \int_{\underline{y}}^{b_C^{RA}-\theta+s} u(w+b_C^{RA}-\theta-y)g(y)dy + \int_{b_C^{RA}-\theta+s}^{\bar{y}} u(w-s)g(y)dy \\ &= \int_{\underline{y}}^{b_C^{RN}-\theta+s} u(w+b_C^{RN}-\theta-y)g(y)dy + \int_{b_C^{RN}-\theta+s}^{\bar{y}} u(w-s)g(y)dy \\ &< G(b_C^{RN}-\theta+s)u(w+b_C^{RN}-\theta-\mathbb{E}[Y \mid \underline{y} \le y \le b_C^{RN}-\theta+s]) + (1-G(b_C^{RN}-\theta+s))u(w-s) \\ &< u(G(b_C^{RN}-\theta+s)(w+b_C^{RN}-\theta-\mathbb{E}[Y \mid \underline{y} \le y \le b_C^{RN}-\theta+s]) + (1-G(b_C^{RN}-\theta+s))(w-s)) \\ &= u(w). \end{aligned}$$

This contradicts Equation (3.5). As $U_C(b_C^{RA})$ increases in b_C^{RA}, in order to fulfill (3.5), it must be that $b_C^{RA} > b_C^{RN}$.

Similarly, for the risk-seeking bidder with $y_C^{RS}(b_C^{RS}) = b_C^{RS} - \theta + s$, it holds that

$$\begin{aligned}
&U_C(b_C^{RS})\\
=&\int_{\underline{y}}^{b_C^{RS}-\theta+s} u(w + b_C^{RS} - \theta - y)g(y)dy + \int_{b_C^{RS}-\theta+s}^{\bar{y}} u(w-s)g(y)dy\\
=&\int_{\underline{y}}^{b_C^{RN}-\theta+s} u(w + b_C^{RN} - \theta - y)g(y)dy + \int_{b_C^{RN}-\theta+s}^{\bar{y}} u(w-s)g(y)dy\\
>&\, G(b_C^{RN}-\theta+s)u(w + b_C^{RN} - \theta - \mathbb{E}[Y \mid \underline{y} \le y \le b_C^{RN} - \theta + s]) + (1 - G(b_C^{RN}-\theta+s))u(w-s)\\
>&\, u(G(b_C^{RN}-\theta+s)(w + b_C^{RN} - \theta - \mathbb{E}[Y \mid \underline{y} \le y \le b_C^{RN} - \theta + s]) + (1 - G(b_C^{RN}-\theta+s))(w-s))\\
=&\, u(w).
\end{aligned}$$

This contradicts Equation (3.5). To fulfill (3.5), it must be that $b_C^{RS} < b_C^{RN}$.

According to Lemma 6, we have

$$\begin{aligned}
&b_N^{RS} + \mathbb{E}[Z] - \tau < b_C^{RS} < b_C^{RN} = b_N^{RN} + \mathbb{E}[Z] - \tau < b_C^{RA} < b_N^{RA} + \mathbb{E}[Z] - \tau\\
\Rightarrow\ &b_N^{RS} < b_N^{RN} < b_N^{RA} \text{ and}\\
&b_C^{RA} - b_C^{RN} < b_N^{RA} - b_N^{RN},\ b_C^{RA} - b_C^{RS} < b_N^{RA} - b_N^{RS},\ b_C^{RN} - b_C^{RS} < b_N^{RN} - b_N^{RS}.
\end{aligned}$$

□

Proof of Proposition 11. Analogous to the calculation of the thresholds in the proof of Proposition 10, we have $y_C^{RN}(p_C) = y_C^{RA}(p_C) = y_C^{RS}(p_C) = p_C - \theta + s$ in scenario C.

In scenario N, the implementation cost threshold of the risk-neutral bidder is determined by

$$\begin{aligned}
&\int_{\underline{z}}^{\bar{z}} u^{RN}(w + p_N - \theta - \tau - y_N^{RN}(p_N) + z)h(z)dz = u^{RN}(w-s)\\
\Rightarrow &w + p_N - \theta - \tau - y_N^{RN}(p_N) + \mathbb{E}[Z] = w - s\\
\Rightarrow &y_N^{RN}(p_N) = p_N - \theta - \tau + \mathbb{E}[Z] + s.
\end{aligned}$$

Assuming $y_N^{RA}(p_N) = y_N^{RN}(p_N)$ and substituting this into the left side of Equation (3.4) we have

$$\begin{aligned}
&\int_{\underline{z}}^{\bar{z}} u(w + p_N - \theta - \tau - y_N^{RA}(p_N) + z)h(z)dz \\
&= \int_{\underline{z}}^{\bar{z}} u(w - s - \mathbb{E}[Z] + z)h(z)dz \\
&< u(w - s - \mathbb{E}[Z] + \mathbb{E}[Z]) = u(w - s).
\end{aligned}$$

This contradicts Equation (3.7). To fulfill (3.7), $y_N^{RA}(p_N)$ must decrease. Thus, $y_N^{RN}(p_N) > y_N^{RA}(p_N)$.

Analogously, by setting $y_N^{RS}(p_N) = y_N^{RN}(p_N)$ we have $\int_{\underline{z}}^{\bar{z}} u(w + p_N - \theta - \tau - y_N^{RS}(p_N) + z)h(z)dz > u(w - s - \mathbb{E}[Z] + \mathbb{E}[Z]) = u(w - s)$, which contradicts Equation (3.7). To fulfill (3.7), $y_N^{RS}(p_N)$ must increase. Thus, $y_N^{RN}(p_N) < y_N^{RS}(p_N)$. □

Proof of Corollary 1. These results follow from the fact that the difference between the implementation costs thresholds at two different price levels is equal to the difference between those two price levels (see Lemma 7 and Lemma 8). Since the gap between the awarded price and the bidder's own indifference price is the same in both scenarios regardless of risk preferences, as shown in Lemma 7, the corresponding shift in thresholds is also identical. As established in Lemma 6, the implementation costs thresholds at the indifference bid is higher (lower) in N than in C for risk-averse (risk-seeking) bidders. This ordering persists after shifting the thresholds by the same amount in both scenarios, resulting in a higher (lower) realization probability in scenario N.

Since $\Delta\theta = \Delta\theta^N$, according to Lemma 8, it follows that, $y_{N,i}^*(p_N) - y_{C,i}^*(p_C) = y_{N,i}^*(b_{N,i}^*) - y_{C,i}^*(b_{C,i}^*)$.

If bidders are risk-neutral, applying Lemma 6 to bidder j yields $p_C = p_N + \mathbb{E}[Z] - \tau$. Moreover, Lemma 6 states that $y_{C,i}^*(b_{C,i}^*) = y_{N,i}^*(b_{N,i}^*)$. Since $y_{N,i}^*(p_N) - y_{C,i}^*(p_C) = y_{N,i}^*(b_{N,i}^*) - y_{C,i}^*(b_{C,i}^*)$, it follows that $y_{C,i}^*(p_C) = y_{N,i}^*(p_N)$.

If bidders are risk-averse, applying Lemma 6 to bidder j yields $p_C < p_N + \mathbb{E}[Z] - \tau$. Moreover, Lemma 6 states that $y_{C,i}^*(b_{C,i}^*) < y_{N,i}^*(b_{N,i}^*)$. Since $y_{N,i}^*(p_N) - y_{C,i}^*(p_C) = y_{N,i}^*(b_{N,i}^*) - y_{C,i}^*(b_{C,i}^*)$, it follows that $y_{C,i}^*(p_C) < y_{N,i}^*(p_N)$.

If bidders are risk-seeking, applying Lemma 6 to bidder j yields $p_C > p_N + \mathbb{E}[Z] - \tau$. Moreover, Lemma 6 states that $y_{C,i}^*(b_{C,i}^*) > y_{N,i}^*(b_{N,i}^*)$. Since $y_{N,i}^*(p_N) - y_{C,i}^*(p_C) = y_{N,i}^*(b_{N,i}^*) - y_{C,i}^*(b_{C,i}^*)$, it follows that $y_{C,i}^*(p_C) > y_{N,i}^*(p_N)$. □

Proof of Proposition 12. For any number and composition of bidders, only the best bidder of each risk type can potentially win the auction, and only the best two bidders of each risk type can possibly determine the auction price. We refer to these potential winners and price setters as the relevant bidders. If exists, let $RA1$ and $RA2$ denote the best and second-best risk-averse bidders, and $RN1$ and $RN2$ the best and second-best risk-neutral bidders, respectively. According to Lemma 7, it holds that $b_C^{RA}(\theta_{RA2}) - b_C^{RA}(\theta_{RA1}) = b_N^{RA}(\theta_{RA2}) - b_N^{RA}(\theta_{RA1}) = \theta_{RA2} - \theta_{RA1}$ and $b_C^{RN}(\theta_{RN2}) - b_C^{RN}(\theta_{RN1}) = b_N^{RN}(\theta_{RN2}) - b_N^{RN}(\theta_{RN1}) = \theta_{RN2} - \theta_{RN1}$. Furthermore, Proposition 10 states that $b_C^{RA}(\theta) - b_C^{RN}(\theta) < b_N^{RA}(\theta) - b_N^{RN}(\theta), \forall\theta$.

There are in total 16 possible combinations of winners and price setters across the two scenarios. Since being the best among bidders of the same risk type is necessary but not sufficient for winning the auction, we only examine the preferences of the potential winners $RA1$ and $RN1$ in each case. Under Assumption 1, the comparison of expected utility in winning case reduce to price differences. That is, $U_C^{RA}(\theta_{RA1}, p_C) \gtrless U_N^{RA}(\theta_{RA1}, p_N)$ iff $p_C - p_N \gtrless b_C^{RA}(\theta_{RA1}) - b_N^{RA}(\theta_{RA1})$ for risk-averse bidders and $U_C^{RN}(\theta_{RN1}, p_C) \gtrless U_N^{RN}(\theta_{RN1}, p_N)$ iff $p_C - p_N \gtrless b_C^{RN}(\theta_{RN1}) - b_N^{RN}(\theta_{RN1})$ for risk-seeking bidders.

1. $RN1$ wins in both C and N, $RN2$ sets the price in both C and N: $p_C - p_N = b_C^{RN}(\theta_{RN2}) - b_N^{RN}(\theta_{RN2}) = b_C^{RN}(\theta_{RN1}) - b_N^{RN}(\theta_{RN1}) \Rightarrow U_C^{RN}(\theta_{RN1}, p_C) = U_N^{RN}(\theta_{RN1}, p_N)$. Thus, $RN1$ is indifferent between C and N. Since $RA1$ does not win, $RA1$ is also indifferent between C and N.

2. $RN1$ wins in both C and N, $RA1$ sets the price in both C and N: $p_C - p_N = b_C^{RA}(\theta_{RA1}) - b_N^{RA}(\theta_{RA1}) = b_C^{RA}(\theta_{RN1}) + \theta_{RN1} - \theta_{RA1} - (b_N^{RA}(\theta_{RN1}) + \theta_{RN1} - \theta_{RA1}) = b_C^{RA}(\theta_{RN1}) - b_N^{RA}(\theta_{RN1}) < b_C^{RN}(\theta_{RN1}) - b_N^{RN}(\theta_{RN1}) \Rightarrow U_C^{RN}(\theta_{RN1}, p_C) < U_N^{RN}(\theta_{RN1}, p_N)$. Thus, $RN1$ prefers N. $RA1$ is indifferent.

3. $RN1$ wins in both C and N, $RA1$ sets the price in C and $RN2$ sets the price in N: $p_C - p_N = b_C^{RA}(\theta_{RA1}) - b_N^{RN}(\theta_{RN2}) < b_C^{RN}(\theta_{RN2}) - b_N^{RN}(\theta_{RN2}) = b_C^{RN}(\theta_{RN1}) - b_N^{RN}(\theta_{RN1}) \Rightarrow U_C^{RN}(\theta_{RN1}, p_C) <$
$U_N^{RN}(\theta_{RN1}, p_N)$. Thus, $RN1$ prefers N. $RA1$ is indifferent.

4. $RN1$ wins in both C and N, $RN2$ sets the price in C and $RA1$ sets the price in N: Here, we have $p_C = b_C^{RN}(\theta_{RN2}) < b_C^{RA}(\theta_{RA1})$ and $p_N = b_N^{RA}(\theta_{RA1}) < b_N^{RN}(\theta_{RN2})$. It follows that $b_C^{RA}(\theta_{RA1}) - b_C^{RN}(\theta_{RN2}) > b_N^{RA}(\theta_{RA1}) - b_N^{RN}(\theta_{RN2}) \Leftrightarrow b_C^{RA}(\theta_{RA1}) - b_C^{RN}(\theta_{RA1}) > b_N^{RA}(\theta_{RA1}) - b_N^{RN}(\theta_{RA1})$, which contradicts Proposition 10. Thus, this case cannot arise.

5. $RA1$ wins in C, $RN1$ wins in N, $RA2$ sets the price in C and $RN2$ sets the price in N: Since $RN1$ only wins in N and $RA1$ only wins in C, $RN1$ prefers N and $RA1$ prefers C.

6. $RA1$ wins in C, $RN1$ wins in N, $RA2$ sets the price in C and $RA1$ sets the price in N: Same as above, $RN1$ prefers N and $RA1$ prefers C.

7. $RA1$ wins in C, $RN1$ wins in N, $RN1$ sets the price in C and $RN2$ sets the price in N: Same as above, $RN1$ prefers N and $RA1$ prefers C.

8. $RA1$ wins in C, $RN1$ wins in N, $RN1$ sets the price in C and $RA1$ sets the price in N: Same as above, $RN1$ prefers N and $RA1$ prefers C.

9. $RN1$ wins in C, $RA1$ wins in N, $RN2$ sets the price in C and $RA2$ sets the price in N: Here, we have $b_C^{RN}(\theta_{RN1}) < b_C^{RA}(\theta_{RA1})$ and $b_N^{RA}(\theta_{RA1}) < b_N^{RN}(\theta_{RN1})$. It follows that $b_C^{RA}(\theta_{RA1}) - b_C^{RN}(\theta_{RN1}) > b_N^{RA}(\theta_{RA1}) - b_N^{RN}(\theta_{RN1}) \Leftrightarrow b_C^{RA}(\theta_{RA1}) - b_C^{RN}(\theta_{RA1}) > b_N^{RA}(\theta_{RA1}) - b_N^{RN}(\theta_{RA1})$, which contradicts Proposition 10. Thus, this case cannot arise.

10. $RN1$ wins in C, $RA1$ wins in N, $RN2$ sets the price in C and $RN1$ sets the price in N: Same as above, this case cannot arise.

11. $RN1$ wins in C, $RA1$ wins in N, $RA1$ sets the price in C and $RA2$ sets the price in N: Same as above, this case cannot arise.

12. $RN1$ wins in C, $RA1$ wins in N, $RA1$ sets the price in C and $RN1$ sets the price in N: Same as above, this case cannot arise.

13. $RA1$ wins in both C and N, $RA2$ sets the price in both C and N: $p_C - p_N = b_C^{RA}(\theta_{RA2}) - b_N^{RA}(\theta_{RA2}) = b_C^{RA}(\theta_{RA1}) - b_N^{RA}(\theta_{RA1}) \Rightarrow U_C^{RA}(\theta_{RA1}, p_C) = U_N^{RA}(\theta_{RA1}, p_N)$. Thus, $RA1$ is indifferent between C and N. $RN1$ is also indifferent.

14. $RA1$ wins in both C and N, $RN1$ sets the price in both C and N: $p_C - p_N = b_C^{RN}(\theta_{RN1}) - b_N^{RN}(\theta_{RN1}) = b_C^{RN}(\theta_{RA1}) - b_N^{RN}(\theta_{RA1}) > b_C^{RA}(\theta_{RA1}) - b_N^{RA}(\theta_{RA1}) \Rightarrow U_C^{RA}(\theta_{RA1}, p_C) > U_N^{RA}(\theta_{RA1}, p_N)$. Thus, $RA1$ prefers C. $RN1$ is indifferent.

15. $RA1$ wins in both C and N, $RA2$ sets the price in C and $RN1$ sets the price in N: $p_C - p_N = b_C^{RA}(\theta_{RA2}) - b_N^{RN}(\theta_{RN1}) > b_C^{RA}(\theta_{RA2}) - b_N^{RA}(\theta_{RA2}) = b_C^{RA}(\theta_{RA1}) - b_N^{RA}(\theta_{RA1}) \Rightarrow U_C^{RA}(\theta_{RA1}, p_C) < U_N^{RA}(\theta_{RA1}, p_N)$. Thus, $RA1$ prefers C. $RN1$ is indifferent.

16. $RA1$ wins in both C and N, $RN1$ sets the price in C and $RA2$ sets the price in N: Here, we have $p_C = b_C^{RN}(\theta_{RN1}) < b_C^{RA}(\theta_{RA2})$ and $p_N = b_N^{RA}(\theta_{RA2}) < b_N^{RN}(\theta_{RN1})$. It follows that $b_C^{RA}(\theta_{RA2}) - b_C^{RN}(\theta_{RN1}) > b_N^{RA}(\theta_{RA1}) - b_N^{RN}(\theta_{RN2}) \Leftrightarrow b_C^{RA}(\theta_{RA2}) - b_C^{RN}(\theta_{RA2}) > b_N^{RA}(\theta_{RA2}) - b_N^{RN}(\theta_{RA2})$, which contradicts Proposition 10. Thus, this case cannot arise.

Now consider the perspective of a risk-neutral bidder. Depending on the value of n, different subsets of the 16 cases listed above can arise. Nevertheless, regardless of n, $RN1$ always weakly prefers N, as N yields weakly higher expected utility for the best risk-neutral bidder. Importantly, competition among risk-neutral bidders depends only on their private cost signal θ, n, or risk types. Hence, the probability of being the lowest-cost risk-neutral bidder is always strictly positive. In addition, risk-neutral bidders have a greater competitive advantage over risk-averse bidders in scenario N relative to in scenario C, leading to a higher winning probability in N. As a result, the expected utility – taking into account both the expected utility in winning case and the winning probability – is higher in N for each risk-neutral bidder, i.e., $EU_C(b_C^*) < EU_N(b_N^*)$.

Analogous reasoning shows that each risk-averse bidder weakly prefers C. Besides, the approximation $U_C(p_C) = U_N(p_N)$ used in Assumption 1 is rather conservative and speaks rather for C, which further supports their preference for C. □

Proof of Proposition 13. Consider first scenario C. Equation (3.6) yields that $y_C^*(b_C^*) = b_C^* - \theta + s$. Substitute the cutoff types into Equation (3.5) for each bidder, we have

$$U_C(b_C^*) = \int_{\underline{y}}^{b_C^*-\theta+s} u(w + b_C^* - \theta - y)g(y)dy + \int_{b_C^*-\theta+s}^{\bar{y}} u(w-s)g(y)dy = u(w),$$

$$\frac{db_C^*}{dw} = -\frac{\int_{\underline{y}}^{b_C^*-\theta+s} u'(w + b_C^* - \theta - y)g(y)dy + \int_{b_C^*-\theta+s}^{\bar{y}} u'(w-s)g(y)dy - u'(w)}{\int_{\underline{y}}^{b_C^*-\theta+s} u'(w + b_C^* - \theta - y)g(y)dy}. \tag{B.9}$$

According to Proposition 10, it hold that $b_C^{RS} < b_C^{RN} < b_C^{RA}$.

If bidders are risk-neutral with $u(x) = x$, the numerator in Line (B.9) is zero and $\frac{db_C^*}{dw} = 0$. So the indifference bid is independent of the wealth level, i.e., $b_{C,i}^{RN} = b_{C,j}^{RN}$ and thus $y_{C,i}^{RN}(b_{C,i}^{RN}) = y_{C,j}^{RN}(b_{C,j}^{RN})$.

If bidders are risk-averse, $u'(x) > 0$ and $u''(x) < 0$. If the Arrow-Pratt measure of absolute risk aversion is non-increasing, it follows that

$$\begin{aligned}
&\frac{d}{dx}\left(-\frac{u''(x)}{u'(x)}\right) \leq 0 \\
\Leftrightarrow &\frac{-u'''(x)u'(x) + (u''(x))^2}{(u'(x))^2} \leq 0 \\
\Leftrightarrow &u'''(x) \geq \frac{(u''(x))^2}{u'(x)} > 0.
\end{aligned}$$

That is, u' is strictly convex. In this case, no general statement can be made. In contrast, if $u'''(x) < 0$, implying a strictly increasing Arrow-Pratt measure of absolute risk aversion, then we have

$$\begin{aligned}
&\int_{\underline{y}}^{b_C^{RA}-\theta+s} u'(w+b_C^{RA}-\theta-y)g(y)dy+\int_{b_C^{RA}-\theta+s}^{\bar{y}} u'(w-s)g(y)dy-u'(w)\\
&< u'\left(\int_{\underline{y}}^{b_C^{RA}-\theta+s}(w+b_C^{RA}-\theta-y)g(y)dy+\int_{b_C^{RA}-\theta+s}^{\bar{y}}(w-s)g(y)dy\right)-u'(w)\\
&< u'\left(\int_{\underline{y}}^{b_C^{RN}-\theta+s}(w+b_C^{RN}-\theta-y)g(y)dy+\int_{b_C^{RN}-\theta+s}^{\bar{y}}(w-s)g(y)dy\right)-u'(w)\\
&= u'(w)-u'(w)=0.
\end{aligned}$$

This implies $\frac{db_C^*}{dw}<0$, i.e., $b_{C,i}^{RA}<b_{C,j}^{RA}$ and thus $y_{C,i}^{RA}(b_{C,i}^{RA})<y_{C,j}^{RA}(b_{C,j}^{RA})$. That is, if bidders are risk-averse and the absolute risk aversion increases in the wealth level, then the indifference bid decreases in the wealth level.

Analogously, if bidders are risk-seeking and $u'''>0$, then $\frac{db_C^*}{dw}>0$, i.e., $b_{C,i}^{RS}>b_{C,j}^{RS}$ and thus $y_{C,i}^{RS}(b_{C,i}^{RS})>y_{C,j}^{RS}(b_{C,j}^{RS})$. That is, if the level of risk-seeking increases in the wealth level, then the bidder with higher wealth level bids more aggressively.

Next, consider scenario N. Equation (3.5) yields that

$$\begin{aligned}
\frac{\partial U_N(b_N^*)}{\partial w}=&\frac{dy_N^*}{dw}\cdot\int_{\underline{z}}^{\bar{z}} u(w+b_N^*-\theta-\tau-y_N^*+z)h(z)dzg(y_N^*)-\frac{dy_N^*}{dw}\cdot u(w-s)g(y_N^*)\\
&+\int_{\underline{y}}^{y_N^*(b_N^*)}\int_{\underline{z}}^{\bar{z}} u'(w+b_N^*-\theta-\tau-y+z)h(z)dzg(y)dy+\int_{y_N^*(b_N^*)}^{\bar{y}} u'(w-s)g(y)dy\\
=&\int_{\underline{y}}^{y_N^*(b_N^*)}\int_{\underline{z}}^{\bar{z}} u'(w+b_N^*-\theta-\tau-y+z)h(z)dzg(y)dy+\int_{y_N^*(b_N^*)}^{\bar{y}} u'(w-s)g(y)dy,
\end{aligned}$$

$$\begin{aligned}
\frac{\partial U_N(b_N^*)}{\partial b_N^*}=&\frac{dy_N^*}{db_N^*}\cdot\int_{\underline{z}}^{\bar{z}} u(w+b_N^*-\theta-\tau-y_N^*+z)h(z)dzg(y_N^*)-\frac{dy_N^*}{db_N^*}\cdot u(w-s)g(y_N^*)\\
&+\int_{\underline{y}}^{y_N^*(b_N^*)}\int_{\underline{z}}^{\bar{z}} u'(w+b_N^*-\theta-\tau-y+z)h(z)dzg(y)dy\\
=&\int_{\underline{y}}^{y_N^*(b_N^*)}\int_{\underline{z}}^{\bar{z}} u'(w+b_N^*-\theta-\tau-y+z)h(z)dzg(y)dy>0,
\end{aligned}$$

$$\frac{db_N^*}{dw}=-\frac{\int_{\underline{y}}^{y_N^*(b_N^*)}\int_{\underline{z}}^{\bar{z}} u'(w+b_N^*-\theta-\tau-y+z)h(z)dzg(y)dy+\int_{y_N^*(b_N^*)}^{\bar{y}} u'(w-s)g(y)dy-u'(w)}{\int_{\underline{y}}^{y_N^*(b_N^*)}\int_{\underline{z}}^{\bar{z}} u'(w+b_N^*-\theta-\tau-y+z)h(z)dzg(y)dy}. \tag{B.10}$$

According to Proposition 10, it hold that $b_N^{RS}<b_N^{RN}<b_N^{RA}$ and $y_N^{RS}(b_N^{RS})<y_N^{RN}(b_N^{RN})<y_N^{RA}(b_N^{RA})$.

If bidders are risk-neutral with $u(x) = x$, the numerator in Line B.10 is zero and $\frac{db_N^*}{dw} = 0$. So the indifference price is independent of the wealth level, i.e., $b_{C,i}^{RN} = b_{C,j}^{RN}$ and thus $y_{C,i}^{RN}(b_{C,i}^{RN}) = y_{C,j}^{RN}(b_{C,j}^{RN})$.

If bidders are risk-averse and $u'''(x) > 0$, no general statement can be made. If $u'''(x) < 0$ for risk-averse bidders, we have

$$\begin{aligned}
&\int_{\underline{y}}^{y_N^{RA}(b_N^{RA})} \int_{\underline{z}}^{\bar{z}} u'(w + b_N^{RA} - \theta - \tau - y + z)h(z)dzg(y)dy + \int_{y_N^{RA}(b_N^{RA})}^{\bar{y}} u'(w-s)g(y)dy - u'(w) \\
< &\int_{\underline{y}}^{y_N^{RA}(b_N^{RA})} u'(w + b_N^{RA} - \theta - \tau - y + \mathbb{E}[Z])g(y)dy + \int_{y_N^{RA}(b_N^{RA})}^{\bar{y}} u'(w-s)g(y)dy - u'(w) \\
< &\, u'\left(\int_{\underline{y}}^{y_N^{RA}(b_N^{RA})} (w + b_N^{RA} - \theta - \tau - y + \mathbb{E}[Z])g(y)dy + \int_{y_N^{RA}(b_N^{RA})}^{\bar{y}} (w-s)g(y)dy\right) - u'(w) \\
< &\, u'\left(\int_{\underline{y}}^{y_N^{RN}(b_N^{RA})} (w + b_N^{RA} - \theta - \tau - y + \mathbb{E}[Z])g(y)dy + \int_{y_N^{RA}(b_N^{RA})}^{\bar{y}} (w-s)g(y)dy\right) - u'(w) \\
= &\, u'(w) - u'(w) = 0.
\end{aligned}$$

This implies $\frac{db_N^*}{dw} < 0$, i.e., $b_{N,i}^{RA} < b_{C=N,j}^{RA}$ and thus $y_{N,i}^{RA}(b_{N,i}^{RA}) < y_{N,j}^{RA}(b_{N,j}^{RA})$. That is, if bidders are risk-averse and the absolute risk aversion increases in the wealth level, then the indifference bid decreases in the wealth level in scenario N as well.

Analogously, if bidders are risk-seeking and $u''' > 0$, then $\frac{db_N^*}{dw} > 0$, i.e., $b_{N,i}^{RS} > b_{N,j}^{RS}$ and thus $y_{N,i}^{RS}(b_{N,i}^{RS}) > y_{N,j}^{RS}(b_{N,j}^{RS})$. □

Proof of Proposition 14. In scenario N, Equation (3.4) yields that

$$\frac{dy_N^*}{dw} = \frac{\int_{\underline{z}}^{\bar{z}} u'(w + p_N - \theta - \tau - y_N^* + z)h(z)dz + u'(w-s)}{\int_{\underline{z}}^{\bar{z}} u'(w + p_N - \theta - \tau - y_N^* + z)h(z)dz}.$$

According to Proposition 11, it hold that $y_N^{RS}(p_N) > y_N^{RN}(p_N) > y_N^{RA}(p_N)$.

If bidders are risk-neutral with $u(x) = x$, the numerator in Line B.10 is zero and $\frac{dy_N^*}{dw} = 0$. So the realization probability is independent of the wealth level, i.e., $y_{N,i}^{RN}(p_N) = y_{N,j}^{RN}(p_N)$. Besides, we have $w + p_N - \theta - \tau - y_N^{RN} + \mathbb{E}[Z] = w - s$.

If bidders are risk-averse and $u'''(x) > 0$, no general statement can be made. If $u'''(x) < 0$

for risk-averse bidders, we have

$$\begin{aligned}
&\int_{\underline{z}}^{\bar{z}} u'(w + p_N - \theta - \tau - y_N^{RA} + z)h(z)dz - u'(w - s) \\
&< u'(w + p_N - \theta - \tau - y_N^{RA} + \mathbb{E}[Z]) + u'(w - s) \\
&< u'(w + p_N - \theta - \tau - y_N^{RA} + \mathbb{E}[Z] - w + s) \\
&< u'(w + p_N - \theta - \tau - y_N^{RN} + \mathbb{E}[Z] - w + s) \\
&= 0.
\end{aligned}$$

This implies $\frac{dy_N^*}{dw} < 0$, i.e., $y_{N,i}^{RA}(p_N) > y_{N,j}^{RA}(p_N)$.

Analogously, if bidders are risk-seeking and $u''' > 0$, then $\frac{dy_N^*}{dw} > 0$, i.e., $y_{N,i}^{RS}(p_N) < y_{N,j}^{RS}(p_N)$.

□

A counter example against revenue equivalence theorem

Consider the simple case where all bidders are risk-neutral with $u(x) = x$ and only scenario C.

In the second-price auction, from Equation (3.6) and Equation (3.5) it follows that

$$\int_{\underline{y}}^{b_C^* - \theta + s} G(y)dy = s.$$

In the symmetric equilibrium, the bidder with the lowest θ wins. Denote the expected private cost of the winning with $\theta_{(1)}$, the expected award price is

$$\mathbb{E}[P_C] = b_C^* + \int_{\theta_{(1)}}^{\bar{\theta}} t f_{(1,n-1)}(t)dt - \theta_{(1)}.$$

Therefore, for the expected revenue of the auctioneer it holds that

$$\int_{\underline{y}}^{\mathbb{E}[P_C] - \int_{\theta_{(1)}}^{\bar{\theta}} t f_{(1,n-1)}(t)dt + s} G(y)dy = s.$$

Under PaB pricing, the award price is equal to the bid of the winning bidder. Consider a bidder with θ, the optimal bid is derived by

$$\max_b EU_C^{PaB}(b) = (1 - F_C(b))U_C(b) + F_C(b)u(w),$$

where $1 - F_C(b)$ denote the winning probability of the bidder with bid b. Thus, the optimal bid b^{PaB} is implicitly given by

$$\int_{\underline{y}}^{b^{PaB}-\theta+s} G(y)dy = s + \frac{1-F_C(b^{PaB})}{f_C(b^{PaB})} G(b^{PaB}-\theta+s).$$

In a symmetric equilibrium, the winning probability of the bidder with θ is $(1-F(\theta))^{n-1} = 1-F_{(1,n-1)}(\theta)$, i.e., $1-F_C(b^{PaB}) = 1-F_{(1,n-1)}(\theta)$ and $f_C(b^{PaB}) = f_{(1,n-1)}(\theta)$. Thus, the expected revenue of the auctioneer $\mathbb{E}[P_C^{PaB}]$ satisfies

$$\int_{\underline{y}}^{\mathbb{E}[P_C^{PaB}]-\theta_{(1)}+s} G(y)dy = s + \frac{1-F_{(1,n-1)}(\theta_{(1)})}{f_{(1,n-1)}(\theta_{(1)})} G(\mathbb{E}[P_C^{PaB}]-\theta_{(1)}+s).$$

Assume that the revenue equivalence theorem applies, then $\mathbb{E}[P_C] = \mathbb{E}[P_C^{PaB}] := p_C$. As a result, it must hold that

$$\begin{aligned}
&\int_{p_C-\int_{\theta_{(1)}}^{\bar{\theta}} tf_{(1,n-1)}(t)dt+s}^{p_C-\theta_{(1)}+s} G(y)dy = \frac{1-F_{(1,n-1)}(\theta_{(1)})}{f_{(1,n-1)}(\theta_{(1)})} G(p_C-\theta_{(1)}+s) \\
\Rightarrow\ &(\int_{\theta_{(1)}}^{\bar{\theta}} tf_{(1,n-1)}(t)dt - \theta_{(1)})G(p_C-\theta_{(1)}+s) \geq \frac{1-F_{(1,n-1)}(\theta_{(1)})}{f_{(1,n-1)}(\theta_{(1)})} G(p_C-\theta_{(1)}+s) \\
\Rightarrow\ &\int_{\theta_{(1)}}^{\bar{\theta}} tf_{(1,n-1)}(t)dt - \theta_{(1)} \geq \frac{1-F_{(1,n-1)}(\theta_{(1)})}{f_{(1,n-1)}(\theta_{(1)})} \\
\Rightarrow\ &\bar{\theta} - \theta_{(1)}F_{(1,n-1)}(\theta_{(1)}) - \int_{\theta_{(1)}}^{\bar{\theta}} F_{(1,n-1)}(t)dt - \theta_{(1)} \geq \frac{1-F_{(1,n-1)}(\theta_{(1)})}{f_{(1,n-1)}(\theta_{(1)})} \\
\Rightarrow\ &f_{(1,n-1)}(\theta_{(1)})\bar{\theta}(1-F_{(1,n-1)}(\theta_{(1)})) - f_{(1,n-1)}(\theta_{(1)})\theta - 1 + F_{(1,n-1)}(\theta_{(1)}) \geq 0.
\end{aligned}$$

This inequality is a necessary but not sufficient condition for the revenue equivalence theorem. This inequality does not hold, for instance, when we normalize $\bar{\theta} = 1$ and $F(\theta) = \theta$ is uniformly distributed. For example, the left side of the inequality is equal to $-\theta_{(1)}$ if $n = 2$ and $(1-\theta_{(1)})(1-5\theta_{(1)}+2\theta_{(1)}^2)$ if $n = 3$. Thus, revenue equivalence theorem does not hold here.

B.3 Design proposal

Proof of Proposition 15. In the basis model without maximum prices, i.e., $\bar{b}_C = \bar{b}_N = \infty$, it holds for all bidders that $b_C^* < \bar{b}_C$ and $b_N^* < \bar{b}_N$, implying $EU_C(b_C^*) > u(w)$ and $EU_N(b_N^*) > u(w)$. As a result, regardless of risk preference or private cost, all bidders have an incentive to participate in both the CfD and the payment auction.

In contrast, under Mechanism $\mathcal{M}$ with $\bar{b}_C < \infty$ and $\bar{b}_N = 0$, it is possible that $b_C^* \geq \bar{b}_C$ and/or $b_N^* \geq \bar{b}_N$. In either auction, if a bidder's indifference bid equals the maximum bid, the winning probability becomes zero and the expected utility equals the utility of the initial wealth: $EU_C(b_C^*) = u(w)$ if $b_C^* = \bar{b}_C$, and $EU_N(b_N^*) = u(w)$ if $b_N^* = \bar{b}_N$. In such cases, the bidder is indifferent between participating and not participating. If the indifference bid exceeds the upper bound, e.g., $b_C^* > \bar{b}_C$ in the CfD auction, then submitting any allowed bid ($b_C \leq \bar{b}_C < b_C^*$) would result in a price below the bidder's indifference bid in the case of winning, leading to an expected utility strictly below $u(w)$. Hence, the bidder has no incentive to participate in the CfD auction. The same reasoning applies for $b_N^* > \bar{b}_N$.

We now consider the following four cases based on the relationship between the bidder's indifference bids and the maximum bids:

Case $b_C^* \leq \bar{b}_C$ and $b_N^* > \bar{b}_N$: The bidder has an incentive to participate only in the CfD auction C. Therefore, the bidder only submits $b_C = b_C^*$, which ensures participation if and only if the CfD auction takes place and abstain from participating in the payment auction. This corresponds to option 1, expressing the acceptance of only the CfD auction.

Case $b_C^* \leq \bar{b}_C$ and $b_N^* \leq \bar{b}_N$: The bidder has an incentive to participate in both auctions and the preference depends on the comparison between the expected utilities. If $EU_C(b_C^*) > EU_N(b_N^*)$, the bidder prefers the CfD auction and thus submits $b_C = b_C^*$ and $b_N = b_N^*$. The submission of both CfD and payment bids ensures participation in either auction but favors the CfD auction, which will be implemented unless another bidder submits only b_N^*. This corresponds to option 2, expressing the acceptance of both auctions but a preference for the CfD auction. If $EU_C(b_C^*) \leq EU_N(b_N^*)$, the bidder prefers the payment auction and submits only $b_N = b_N^*$, ensuring the preferred payment auction taking place. This corresponds to option 3, which initiates the payment auction.

Case $b_C^* > \bar{b}_C$ and $b_N^* \leq \bar{b}_N$: The bidder has an incentive to participate only in the payment auction. Therefore, the bidder only submits $b_N = b_N^*$, which initiates the payment auction. This corresponds to option 3.

Case $b_C^* > \bar{b}_C$ and $b_N^* > \bar{b}_N$: The bidder has no incentive to participate in either auction and thus submits no bid. This corresponds to option 4.

In sum, if a bidder only accepts one of both auctions (a CfD under the maximum price or the market solution), it submits the indifferent bid only for that auction; if the bidder accepts both auctions and prefers the CfD auction, it submits both the CfD and the payment indifferent bids to ensure participation in either auction while signaling a preference for the CfD auction; if the bidder accepts both auctions and prefers the payment auction, it submits only the payment indifferent bid to initiate the payment auction; if the bidder accepts none of the auctions, it submits no bid. No bidder has an incentive to deviate from this strategy. Therefore, mechanism $\mathcal{M}$ is incentive-compatible. □

Proof and generalization of Lemma 10. According to Proposition 9, regardless of risk preference, a bidder with τ_ℓ prefers the payment auction, while a bidder with τ_h prefers the CfD auction, provided the bidder is willing to participate in both auctions. With finite maximum prices $\bar{b}_C$ and $\bar{b}_N$, however, both auctions may exclude bidders – though possibly a different number in each. If only one bidder participates in an auction, the awarded price will be the respective maximum price; in the other auction, the awarded price may either be the respective maximum price or be set by another bidder. As a result, the expected utilities of the bidders across the two auction formats are not clearly comparable in general.

Nevertheless, we assume that that the impact of the maximum prices on bidders' expected utilities does not systematically differ between the CfD auction and the payment auction in expectation and therefore does not alter the preferences stated in Proposition 9. This assumption is particularly plausible when either $\Delta\tau$ or n are large. If $\Delta\tau$ is sufficiently large, the advantage of bidders with τ_ℓ over bidders with τ_h in the payment auction becomes so substantial that, regardless of maximum prices, bidders with τ_ℓ will always prefer the payment auction, while bidders with τ_h will always prefer the CfD auction. If n is sufficiently large, the probability that only one bidder participates in either auction converges to zero. In this case, the probability that the awarded price in either auction is set by the respective maximum price also converges to zero, so that the impact of the maximum prices are negligible.

Therefore, we proceed under the assumption that the preferences stated in Proposition 9 hold regardless of the presence of maximum prices. Consequently, a bidder with τ_ℓ will never prefer the CfD auction if $b_N^* \leq \bar{b}_N$ and a bidder with τ_h will never prefer the payment auction if $b_C^* \leq \bar{b}_C$.

Under the assumption $\hat{\theta}_C > \hat{\theta}_{N,\ell}$, the second part of case 3 in Proposition 15, – namely $b_C^* > \bar{b}_C$ and $b_N^* \leq \bar{b}_N$ – cannot occur. Consequently, bidders with τ_h, who prefer the CfD auction as long as $b_C^* \leq \bar{b}_C$, will never submit only a payment bid, and the payment auction can only be initiated by a bidder with τ_ℓ and $b_N^* \leq \bar{b}_N$.

Without assuming $\hat{\theta}_C > \hat{\theta}_{N,\ell}$, the case $b_C^* > \bar{b}_C$ and $b_N^* \leq \bar{b}_N$ can occur. For example, if the bidder can accept the market solution but not the CfD because the CfD maximum price is set too low. Thus, a bidder with τ_h can also initiate the payment auction if and only if $b_C^* > \bar{b}_C$ and $b_N^* \leq \bar{b}_N$. The three possible outcomes of $\mathcal{M}$ and their probabilities are adapted as follows:

(i) If (a) there is at least one bidder with τ_ℓ and $b_N^* \leq \bar{b}_N$, or (b) there is at least one bidder with τ_h and $b_C^* > \bar{b}_C$ and $b_N^* \leq \bar{b}_N$, the payment auction will take place.

The probability of (a) is

$$\sum_{m=0}^{n-1} \binom{n}{m} \varrho^m (1-\varrho)^{n-m} (1-(1-F(\hat{\theta}_{N,\ell}))^{n-m}) = 1 - [\varrho + (1-\varrho)(1-F(\hat{\theta}_{N,\ell}))]^n.$$

The probability of (b) is

$$\begin{aligned}&\sum_{m=1}^{n}\binom{n}{m}\varrho^m(1-\varrho)^{n-m}\big[1-\min\{(1-F(\hat\theta_{N,h})+F(\hat\theta_C))^m,1\}\big]\\ =&1-\big[\varrho\cdot\min\{1-F(\hat\theta_{N,h})+F(\hat\theta_C),1\}+(1-\varrho)\big]^n.\end{aligned}$$

The probability of (a) $\wedge$ (b) is

$$\begin{aligned}&\sum_{m=1}^{n-1}\binom{n}{m}\varrho^m(1-\varrho)^{n-m}\big[1-\min\{(1-F(\hat\theta_{N,h})+F(\hat\theta_C))^m,1\}\big]\cdot\big[1-(1-F(\hat\theta_{N,\ell}))^{n-m}\big]\\ =&1-\big[\varrho\cdot\min\{1-F(\hat\theta_{N,h})+F(\hat\theta_C),1\}+(1-\varrho)\big]^n-[\varrho+(1-\varrho)(1-F(\hat\theta_{N,\ell}))]^n\\ &+\big[\varrho\cdot\min\{1-F(\hat\theta_{N,h})+F(\hat\theta_C),1\}+(1-\varrho)(1-F(\hat\theta_{N,\ell}))\big]^n.\end{aligned}$$

The probability of (a) $\vee$ (b), i.e., the probability that the payment auction takes place, is

$$1-\big[\varrho\cdot\min\{1-F(\hat\theta_{N,h})+F(\hat\theta_C),1\}+(1-\varrho)(1-F(\hat\theta_{N,\ell}))\big]^n.$$

(ii) If all bidders have $b_C^*>\bar b_C$ and $b_N^*>\bar b_N$, there will be no participant. The probability of this case is

$$\big[\varrho(1-F(\max\{\hat\theta_C,\hat\theta_{N,h}\}))+(1-\varrho)(1-F(\max\{\hat\theta_C,\hat\theta_{N,\ell}\}))\big]^n.$$

(iii) In all other cases, the CfD auction will take place. The probability is

$$\begin{aligned}&\big[\varrho\cdot\min\{1-F(\hat\theta_{N,h})+F(\hat\theta_C),1\}+(1-\varrho)(1-F(\hat\theta_{N,\ell}))\big]^n\\ &-\big[\varrho(1-F(\max\{\hat\theta_C,\hat\theta_{N,h}\}))+(1-\varrho)(1-F(\max\{\hat\theta_C,\hat\theta_{N,\ell}\}))\big]^n.\end{aligned}$$

□

Proof of Proposition 16. We consider the three cases from Lemma 10:

(i) If $\mathcal{M}$ results in the payment auction (N auction), we distinguish three subcases:

(a) If at least one bidder with τ_h satisfies $b_N^*\le\bar b_N$, the auction in N includes a mix of bidders with τ_ℓ and τ_h, while the CfD auction (C auction) may include additional bidders with $b_N^*>\bar b_N$ and $b_C^*\le\bar b_C$. These bidders are weaker than those who participate in both the in the N auction and the C auction and can thus neither win nor set the price in the C auction. Therefore, their existence has no effect on the auction outcome. Consider only the bidders who participate in both auctions, according to Proposition 8, the dispersion in τ improves the realization probability in N compared to C. Hence, mechanism $\mathcal{M}$ selects the auction with the higher realization probability.

(b) If no bidder with τ_h satisfies $b_N^* \leq \bar{b}_N$, then only bidders with τ_ℓ (i.e., whose private cost signals satisfy $\theta \leq \hat{\theta}_{N,\ell} < \hat{\theta}_C$) participate in the N auction, while the C auction may also include additional bidders with τ_h with $b_C^* \leq \bar{b}_C$ (i.e., whose private cost signals satisfy $\hat{\theta}_{N,h} < \theta \leq \hat{\theta}_C$). Thus, the competition is more intense in C, but the additional bidders are expected to be weaker than those bidders in N. First, consider the case in which at least two bidders with τ_ℓ participate in the N auction. According to Corollary 1, if bidders are risk-neutral, the realization probability is identical in C and N; if bidders are risk-averse, the realization probability is higher in N. In addition, the increased competition in C due to additional bidders with τ_h reduces the expected difference in indifference bids between the winner and the price setter, thereby lowering the realization probability in C. Therefore, $\mathcal{M}$ selects the auction with the higher realization probability. Second, if only one bidder participates in the N auction, the awarded price is $\bar{b}_N$. In contrast, the C auction may include additional bidders with τ_h, so that the awarded price is determined by a bid. However, as stated in Section 3.7, for a bidder with τ_ℓ who wins in both C and N, the maximum prices do not affect the realization probability in N being larger than in C if $\Delta\tau$ or n are sufficiently large. Together with the arguments in the first case, it follows that, from the auctioneer's perspective, the realization probability in N is larger than in C. Therefore, $\mathcal{M}$ selects the auction with the higher realization probability.

(ii) In this case, no bidder participates in either auction. As a result, the choice of $\mathcal{M}$ is irrelevant.

(iii) If the conditions in cases (i) or (ii) from Lemma 10 are not met, $\mathcal{M}$ results in the CfD auction, we distinguish two subcases:

(a) If at least one bidder with τ_h satisfies $b_N^* \leq \bar{b}_N$, all participants in the payment auction have τ_h (i.e., whose private cost signals satisfy $\theta \leq \hat{\theta}_{N,h} < \hat{\theta}_{N,\ell}$). The CfD auction may include additional bidders with τ_ℓ (i.e., whose private cost signals satisfy $\hat{\theta}_{N,\ell} < \theta \leq \hat{\theta}_C$), who are weaker than those with τ_h and thus cannot win. However, one of these bidders with τ_ℓ may become price setter in the CfD auction if exactly one bidder with τ_h satisfies $b_N^* \leq \bar{b}_N$. Consider first only bidders with τ_h and assume that there are at least two such bidders, according to Corollary 1, if bidders are risk-neutral, then the realization probability is identical in C and N; if bidders are risk-averse, the realization probability is higher in N. In addition, bidders with τ_ℓ may lower the awarded price in C and thus reduce the realization probability. Therefore, $\mathcal{M}$ selects the auction with the lower realization probability. The probability of subcase (iii a) is $\sum_{k=0}^{n} \binom{n}{k} \varrho^k (1-\varrho)^{n-k} [1-(1-F(\hat{\theta}_{N,h}))^k](1-F(\hat{\theta}_{N,\ell}))^{n-k} = [\varrho + (1-\varrho)(1-F(\hat{\theta}_{N,\ell}))]^n - [\varrho(1-F(\hat{\theta}_{N,h})) + (1-\varrho)(1-F(\hat{\theta}_{N,\ell}))]^n$.

Similar to the subcase (i b), if only one bidder with τ_ℓ participates in the payment auction, we assume that the impact of the maximum prices on realization probabilities does not systematically differ between C and N in expectation and therefore does not alter the results above.

(b) If no bidder with τ_h satisfies $b_N^* \leq \bar{b}_N$, then no bidder participates in the payment auction. Therefore, by selecting C, $\mathcal{M}$ ensures participation and thus also a higher realization probability.

In summary, except for subcase (iii a), mechanism $\mathcal{M}$ selects the auction with the higher realization probability. Subcase (iii a) arises when no bidder with τ_ℓ satisfies $b_N^* \leq \bar{b}_N$ but at least one bidder with τ_h does.

□

Appendix C

Appendix to Chapter 4

C.1 Illustration of properties of the GVA

The structure of the following example is based on that of the example in Section 4.2.1. The auction is a forward auction for two similar offshore sites. If ties between optimal allocations occur, the auction breaks them randomly. Table C.1 shows for the basic example the valuations and thus the bids according to the dominant strategy.

Table C.1: Example of valuations and bids (in million €) for two similar offshore wind sites, A and B, that are auctioned off in a forward auction to illustrate properties of the GVA.

	A	B	A & B
Bidder 1	100	100	100
Bidder 2	100	100	100
Bidder 3	0	0	100

Instances of low prices. The GVA assigns one site to each of bidders 1 and 2 because they submit the feasible bid-price combination with a total of 200. Assume that Bidder 1 wins A and Bidder 2 wins B. In the GVA, the price to be paid by a winning bidder is calculated as the difference between the sum of the bid prices in the winning bid combination in a virtual GVA in which the bidder does not participate and the sum of bid prices of the other bidders' winning bids in the actual auction. Hence, the price for each of the two winning bidders 1 and 2 is $100 - 100 = 0$. Thus, the GVA assigns one site to each of the bidders 1 and 2 at a price of zero, while the losing Bidder 3 is willing to pay more than zero. Explaining such low prices to the public can be challenging for the auctioneer. Auctions in which winning bidders pay at least as much as other (sets of) bidders have offered to pay are called core-selecting auctions, which include the PaB auction (Day and Milgrom, 2008).

Non-monotonicity of revenue. If the bid prices of Bidder 1 for A, B, and A & B decreased from 100 to 50, or Bidder 1 did not participate, the auctioneer's revenue would rise from 0 to 50 or 100, respectively. Such non-monotonicity in bidders may occur only with complements but the non-monotonicity in bid prices can even occur with substitutes (Ausubel and Milgrom, 2006; Ott, 2009). Thus, the auctioneer may profit from rejecting bidders or bids.

Different prices for homogeneous items. Let Bidder 1 bid (100, 100, 100), Bidder 2 bid (150, 150, 200), and Bidder 3 bid (0, 0, 100) for A, B, and A & B, respectively. Bidders 1 and 2 each win one site. Bidder 1 has to pay 50 and Bidder 2 has to pay 0, even though the sites are equivalent and Bidder 1 bids less than Bidder 2, which may be considered as a violation of *fairness*.

Cooperation to win at low prices by bidding high. Assume Bidder 3 in Table C.1 is willing to pay 210 for both sites A & B rather than just 100. Then – given truthful bids – Bidder 3 wins the auction. If, however, the two losing bidders 1 and 2 cooperate and each bids 210 for a single site, they will win both sites at a price of zero.

Participating with multiple identities. If Bidder 1 in Table C.1 did not participate and Bidder 3 won, Bidder 2 could benefit by participating with multiple identities as Bidder 2a and Bidder 2b, each bidding an amount of 100 for each site and the package. Then Bidder 2 would win both sites for free.

No dominant strategy with budget restrictions. Assume there are two bidders, 1 and 3. Bidder 1 is interested in only one site and has a valuation of 100. Bidder 3 has a valuation of 100 for each site and of 250 for both sites. Without budget restrictions, Bidder 3 wins both sites, pays 100 and has a profit of 150. If Bidder 3 was restricted to a budget of 180 and thus only bid 180 for both sites, then Bidder 3 would win only one site and its profit would fall to 100. By bidding 0 for the single sites and 180 for both sites, Bidder 3 could maintain its profit of 150. Thus, bidding the maximum of the budget and the valuation may not be optimal, and bidding the valuation may be neither possible (if the bidder is not allowed to bid above budget) nor optimal (because the price might be above budget).

Reserve prices. Auctioneers often use reserve prices to set a lower bound on revenues, to internalize opportunity costs of alternate sales, to optimize the auctioneer's revenues, or to reduce bidders' gains from strategically withholding competition (see, e.g., Myerson, 1981; Ausubel and Baranov, 2017). In a GVA, one can implement lower bounds on prices while sustaining incentives to bid valuations and an efficient outcome by adding a virtual "reserve bidder" for each item (Ausubel and Baranov, 2017). Note that lower bounds on bid prices do not guarantee lower bounds on prices and revenues because prices can fall below the bid prices.

C.2 Bidding incentives and non-realization risk in CAs for RE

This section analyzes the effects of selected design elements on bidding incentives, efficiency, and project realization. Considered are the two bid formats *package bid price* and *component bid prices* (cf. Section C.2.2), and the GVA and PaB pricing rules (cf. Section 4.2.2). Throughout, the superscripts V and P refer to the GVA and the PaB auction, respectively. We analyze reverse auctions because the issues addressed more likely occur in reverse auctions for RE support for onshore technologies. Thus, the allocation with the lowest bid prices wins.

C.2.1 Model framework

Consider a developer with two projects A and B with installed (peak) power P_A and P_B [MW]. The developer estimates the projects to generate $W_A = e_A P_A$ and $W_B = e_B P_B$ [MWh/a] of energy per year during the support period of T years, where e_A and e_B [h/a] denote the annual full load hours of A and B. The developer's project comparison factor is defined as $a = e_A/e_B$. The projects' annualized costs per energy unit are c_A and c_B [ct/kWh] (ct is used to abbreviate € cent). Synergies between the two projects can be modeled such that the costs of one project are higher if the other project is not realized. The developer participates in a CA for RE that allocates support via CfDs for T years to the winning bidders. The derived results apply in principle to support schemes other than the CfD as well. The expected annualized costs per year are $c_A W_A + c_B W_B$ [€/a]. Thus, if the developer receives a payment per energy unit equal to c_A and c_B, the expected profit from the realized combination of the projects A and B is equal to zero.

In the CA, capacity is put out to tender. Developers may submit one-project bids or package bids for multiple projects using the typical RE bid format, i.e., project capacity [MW] and energy bid prices [ct/kWh] (cf. Section 4.3.2). The auctioneer sets a minimum bid price $\underline{b} \geq 0$ and a maximum bid price $\bar{b} > \underline{b}$. Winning bids are determined by the allocation with the lowest sum of weighted bid prices (see sections 4.2.2 and 4.3.2). The weighting depends on the dimension into which the auctioneer converts the capacities of the projects in the bids. On this basis, the auctioneer determines a conversion factor $\hat{q}_j$ for each project j. In case of capacity as dimension, $\hat{q}_j = 1$ for all projects. In case of energy, the auctioneer uses different factors for projects depending on their estimated output, e.g., $\hat{q}_j$ are the annual full load hours depending on the technology or wind class estimated by the auctioneer. Thus, the auctioneer weights the capacities P_A and P_B in the developer's package bid by $\hat{q}_A$ and $\hat{q}_B$. For the following analyses, we neither specify the dimension nor the factors $\hat{q}_A$ and $\hat{q}_B$. The only relevant parameter is the auctioneer's project comparison factor $\hat{a} = \hat{q}_A/\hat{q}_B$. When $\hat{a} < a$, the auctioneer weights project A relatively lower than project B as compared to the developer. For $\hat{a} > a$, it is the other way around.

C.2.2 Package bid price vs. component bid prices

As described in Section 4.2, the general rules of the CA provide that a package bid contains only one bid price, even if the package contains more than one item. We refer to this as the *package bid price* format.

In practice, often a bid price must be submitted for each component of a package bid (see, e.g., Section 4.4.3). We refer to this as the *component bid price* format. One advantage of this format for the bidders the and auctioneer is the precise allocation of bid prices and, thus, support to individual projects.

Package bid price

In the package bid price format, the developer's package bid for A and B is denoted by β_{AB} and includes the capacities P_A and P_B of the two projects and one package bid price b:

$$\beta_{AB} = (P_A, P_B, b)\,.$$

In the PaB auction, a winning bid is paid a price equal to b, while in the GVA, a winning bid is paid a price p that is (weakly) larger than b, i.e., $p \geq b$.

Component bid prices

In the component bid price format, the package bid is denoted by γ_{AB} and includes the two capacities P_A and P_B and two component bid prices b_A and b_B, one for project A and one for project B:

$$\gamma_{AB} = ((P_A, b_A), (P_B, b_B))\,. \tag{C.1}$$

To determine the winning allocation, the auctioneer uses $\hat{q}_A$ and $\hat{q}_B$ or $\hat{a}$ to calculate the weighted average of the bid prices, which is denoted by $\hat{b}(\gamma_{AB})$ and is given by

$$\hat{b}(\gamma_{AB}) = \frac{\hat{q}_A P_A b_A + \hat{q}_B P_B b_B}{\hat{q}_A P_A + \hat{q}_B P_B} = \frac{\hat{a} P_A b_A + P_B b_B}{\hat{a} P_A + P_B}\,.$$

Note that the lower $\hat{b}(\gamma_{AB})$, the higher is the winning probability of γ_{AB}.

For the component bid price format, it is necessary to specify the payments the developer will receive for A and B if the package bid γ_{AB} in (C.1) wins. For PaB pricing, the payment to A (i.e., payment per unit of energy produced by A) is b_A and that to B is b_B, i.e., $p_A = b_A$ and $p_B = b_B$. For the GVA, various options are conceivable. We apply the following rule. If bid γ_{AB} wins at price p (where $p \geq \hat{b}(\gamma_{AB})$), for every energy unit produced by A and B, the developer receives the payments

$$\begin{aligned} p_A &= b_A + p - \hat{b}(\gamma_{AB})\,, \\ p_B &= b_B + p - \hat{b}(\gamma_{AB})\,. \end{aligned} \tag{C.2}$$

Thus, the developer receives the same markup $p - \hat{b}(\gamma_{AB})$ on both bids, i.e., for each unit of energy produced by A, the developer receives b_A plus $p - \hat{b}(\gamma_{AB})$ and for each unit of energy produced by B, the developer receives b_B plus $p - \hat{b}(\gamma_{AB})$.

The rule in (C.2) has the following properties: (i) The payment to a project is at least as high as the bid for this project, i.e., $p_A \geq b_A$ and $p_B \geq b_B$; (ii) The payment for a higher bid is at least as high as that for a lower bid, i.e., $p_A \leq p_B$ if $b_A \leq b_B$; (iii) The auctioneer's weighted average of the prices p_A and p_B paid to the projects is equal to the price p at which the package bid wins. Note that the distorting incentives derived below also apply to rules other than (C.2) with properties (i)–(iii).

C.2.3 Bidding incentives

We now analyze the bidding incentives generated by the design. For simplicity, we assume that the developer submits only a package bid for projects A and B but no single-project bids. In addition, we assume that the developers will realize the awarded projects. The non-realization risk is considered separately in Section C.2.4.

Package bid price

A winning bid $\beta_{AB} = (P_A, P_B, b)$ receives a price p determined by the pricing rule. If the developer receives the payment p for each unit of energy produced by the projects A and B, the annualized profit is

$$\pi(p) = (p - c_A)W_A + (p - c_B)W_B\,.$$

In the GVA, $p \geq b$. The developer's beliefs about winning, i.e., the developer's subjective probability that β_{AB} will win at price p, is captured by the distribution function G with the density function g. Thus, the developer's expected annualized profit with bid b is

$$\Pi^V(b) = \int_b^{\bar{b}} \pi(p)g(p)dp\,. \tag{C.3}$$

Maximizing (C.3) with respect to b yields the optimal bid

$$b^V = \frac{c_A W_A + c_B W_B}{W_A + W_B} = \frac{a c_A P_A + c_B P_B}{a P_A + P_B}\,, \tag{C.4}$$

where b^V is the energy-weighted average of c_A and c_B. b^V lies between c_A and c_B and bidding

b^V is a weakly dominant strategy. The developer tells the truth with b^V in the sense that b^V is the price at which the developer has zero profit, i.e., is indifferent between winning and not winning. This applies even if $\hat{a} \neq a$.

In the PaB auction, $p = b$. The developer's beliefs about winning with b are captured by the distribution function $\hat{H}$ and the density function $\hat{h}$. Thus, the developer's expected annualized profit with the bid b is

$$\Pi^P(b) = (1 - \hat{H}(b))\pi(b) = (1 - \hat{H}(b))((b - c_A)W_A + (b - c_B)W_B)\,.$$

Solving the first-order condition, the optimal bid b^P is given by

$$b^P = \frac{c_A W_A + c_B W_B}{W_A + W_B} + \frac{1 - \hat{H}(b^P)}{\hat{h}(b^P)} = \frac{a c_A P_A + c_B P_B}{a P_A + P_B} + \frac{1 - \hat{H}(b^P)}{\hat{h}(b^P)} \geq b^V,$$

where $\frac{1-\hat{H}(b^P)}{\hat{h}(b^P)}$ is the mark-up.

If $\hat{a} = a$, truthful bids in the GVA and the truthful bids with a mark-up in the PaB auction will lead to an efficient outcome. If $\hat{a} \neq a$, the developer's calculus and the auctioneer's bid evaluation are inconsistent. Thus, both the GVA and the PaB auction may lead to inefficient outcomes.

Component bid prices

A winning bid $\gamma_{AB} = ((P_A, b_A), (P_B, b_B))$ is paid p_A and p_B determined by the pricing rule. If the developer receives p_A and p_B for each unit of energy produced by the projects A and B, respectively, the annualized profit is

$$\pi(p_A, p_B) = (p_A - c_A)W_A + (p_B - c_B)W_B = e_B\left((p_A - c_A)aP_A + (p_B - c_B)P_B\right).$$

In the GVA, if γ_{AB} wins at p, $p \geq \hat{b}(\gamma_{AB})$, then $p_A = b_A + p - \hat{b}(\gamma_{AB})$ and $p_B = b_B + p - \hat{b}(\gamma_{AB})$. The developer's expected profit with b_A and b_B is

$$\Pi^V(b_A, b_B) = \int_{\hat{b}(\gamma_{AB})}^{\bar{b}} \pi(p_A, p_B) g(p) dp\,. \tag{C.5}$$

The derivatives of (C.5) with respect to b_j, $j \in \{A, B\}$, can be written as

$$\frac{\partial \Pi^V(\cdot)}{\partial b_A} = e_B \frac{-\hat{a}P_A\left[(b_A - c_A)aP_A + (b_B - c_B)P_B\right] g(\hat{b}(\gamma)) + (a - \hat{a})P_A P_B(1 - G(\hat{b}(\gamma)))}{\hat{a}P_A + P_B},$$
$$\frac{\partial \Pi^V(\cdot)}{\partial b_B} = e_B \frac{-P_B\left[(b_A - c_A)aP_A + (b_B - c_B)P_B\right] g(\hat{b}(\gamma)) + (\hat{a} - a)P_A P_B(1 - G(\hat{b}(\gamma)))}{\hat{a}P_A + P_B}.$$

Maximizing (C.5) with respect to b_A and b_B yields the first-order conditions $\frac{\partial \Pi^V(\cdot)}{\partial b_A} = 0$ and $\frac{\partial \Pi^V(\cdot)}{\partial b_B} = 0$. The bids $b_A^V = c_A$ and $b_B^V = c_B$ can simultaneously satisfy the two first-order conditions only if $\hat{a} = a$. For $\hat{a} \neq a$, the truthful bids $b_A^V = c_A$ and $b_B^V = c_B$ may not be optimal. More precisely, if $\hat{a} < a$ (i.e., the auctioneer overestimates energy production of B), the developer has an incentive for $b_A > c_A$ and $b_B < c_B$ and to spread b_A and b_B as much as possible so that either $b_B = \underline{b}$ or $b_A = \bar{b}$. For $\hat{a} > a$, the converse holds: $b_A < c_A$ and $b_B > c_B$.

The following example illustrates the bidding incentive to spread the bids.

Example 1. *The developer's projects A and B are characterized by $P_A = 10$ MW, $P_B = 10$ MW, $c_A = 2$ ct/kWh, and $c_B = 4$ ct/kWh. The developer's project comparison factor is $a = 2$. Take a CA as GVA with component bid pricing.*

If the developer submits the truthful bid γ_{AB}^V, with $b_A^V = c_A$ and $b_B^V = c_B$, the weighted average bid price b_w becomes

$$b_w = \frac{aP_A c_A + P_B c_B}{aP_A + P_B} = 2.67 \ ct/kWh.$$

The auctioneer sets the minimum bid price to 0 and the maximum bid price to 5 ct/kWh and estimates the project comparison factor $\hat{a} = 1 < a$. Then

$$\hat{b}(\gamma_{AB}^V) = \frac{\hat{a}P_A c_A + P_B c_B}{\hat{a}P_A + P_B} = 3 \ ct/kWh,$$

which is higher than b_w. Remember: the lower $\hat{b}(\gamma_{AB})$, the higher the winning probability. That is, the auctioneer evaluates the component bid worse than it is, given the underlying costs.

A developer who maximizes expected profit will submit a combination of bid prices where $b_A \gg b_B$. Either b_B is equal to the minimum bid price or b_A is equal to the maximum bid price, so that γ_{AB} has a higher winning probability and a higher profit in case of winning than the truthful bid γ_{AB}^V.

If the developer maximizes the probability of winning while receiving at least the profit of the truthful bid γ_{AB}^V in case of winning, it minimizes $\hat{b}(\gamma_{AB})$ with the bid prices b_A and b_B under the conditions $b_A \geq c_A$ and $b_w = 2.67$ ct/kWh. This leads to $b_A = 4$ ct/kWh and $b_B = 0$ ct/kWh (i.e., the minimum bid price), resulting in $\hat{b}(\gamma_{AB}) = 2$ ct/kWh, which is lower than the bid price $\hat{b}(\gamma_{AB}^V) = 3$ ct/kWh of the truthful bid.

If the developer maximizes the profit in case of winning while maintaining the winning probability of the truthful bid γ_{AB}^V, it maximizes the profit with the bid prices b_A and b_B under the condition $\hat{b}(\gamma_{AB}) = 3$ ct/kWh. This is achieved by $b_A = 5$ ct/kWh (i.e., the maximum bid price) and $b_B = 1$ ct/kWh.

Note that the bid spread is independent of the costs of the projects; it depends only on the ratio of $\hat{a}$ and a. In Example 1, the developer submits the lower bid for the more expensive project B. Thus, the GVA is likely to generate an inefficient outcome under the component bid price rule if $\hat{a} \neq a$. If $\hat{a} \neq a$, the incentive to spread b_A and b_B and the inefficiency problem also apply in the PaB auction.

In the PaB auction, if bid γ_{AB} wins, then $p_A = b_A$ and $p_B = b_B$. Thus, the developer's expected profit with b_A and b_B is

$$\Pi^P(b_A, b_B) = \left(1 - \hat{H}(\hat{b}(\gamma_{AB}))\right) \pi(b_A, b_B) \,.$$

The derivatives with respect to b_j, $j \in \{A, B\}$, can be written as

$$\frac{\partial \Pi^P(\cdot)}{\partial b_A} = e_B \frac{-P_A \left[\hat{h}(\hat{b}(\gamma))\hat{a}((b_A - c_A)aP_A + (b_B - c_B)P_B) + (1 - \hat{H}(\hat{b}(\gamma)))a(\hat{a}P_A + P_B)\right]}{\hat{a}P_A + P_B},$$
$$\frac{\partial \Pi^P(\cdot)}{\partial b_B} = e_B \frac{-P_B \left[\hat{h}(\hat{b}(\gamma))((b_A - c_A)aP_A + (b_B - c_B)P_B) + (1 - \hat{H}(\hat{b}(\gamma)))(\hat{a}P_A + P_B)\right]}{\hat{a}P_A + P_B}.$$

Similar as in the GVA, $b_A^P = c_A + \frac{1-\hat{H}(\hat{b}(\gamma))}{\hat{h}(\hat{b}(\gamma))}$ and $b_B^P = c_B + \frac{1-\hat{H}(\hat{b}(\gamma))}{\hat{h}(\hat{b}(\gamma))}$ can simultaneously fulfill the first-order conditions only if $\hat{a} = a$. If $\hat{a} < a$, the developer has an incentive to spread the bids, i.e., $b_A^P > c_A + \frac{1-\hat{H}(\hat{b}(\gamma))}{\hat{h}(\hat{b}(\gamma))}$ and $b_B^P < c_B + \frac{1-\hat{H}(\hat{b}(\gamma))}{\hat{h}(\hat{b}(\gamma))}$, so that either $b_B^P = \underline{b}$ or $b_A^P = \bar{b}$. For $\hat{a} > a$ it is the other way round.

C.2.4 Non-realization risk

This section examines the non-realization risk of awarded projects in a CA, i.e., developers submit package bids that include projects that will not be realized if the package bid wins. Unlike the bidding incentives in Section C.2.3, for both bid formats this risk exists not only for $\hat{a} \neq a$, but also for $\hat{a} = a$. Thus, the results also apply to (forward and reverse) CAs that result in fixed payments, such as auctions of wind rights.

Package bid price

Both the GVA and the PaB auction with package bid prices may cause a non-realization risk if $c_A \neq c_B$. According to (C.4), it is optimal to submit the truthful bid b^V, which lies between c_A and c_B, in the GVA. Thus, in case of winning, it is possible that p is smaller than the larger of the project costs. Then the developer may have an incentive not to realize the more expensive project. The non-realization risk also exists under PaB pricing.

Component bid prices

In the case of non-realization, the developer typically has to pay a penalty $s > 0$ per MW of peak power P of the unrealized project, i.e., sP in total (e.g., EEG, 2023, § 36a). For ease of illustration, we assume that costs c_A and c_B do not depend on the realization of the other project. For simplicity, let $P = P_A = P_B$, $e = e_A = e_B$, $a = \hat{a} = 1$, and $c = c_A = c_B$ with $c \geq (\bar{b} + \underline{b})/2$. Analogously, the following results also apply if $c < (\bar{b} + \underline{b})/2$.

In the GVA, the optimal package bid $\gamma_{AB}^V = ((P_A, b_A^V), (P_B, b_B^V))$ has the average bid price

$$b_w = \frac{b_A^V + b_B^V}{2} = c\,. \tag{C.6}$$

Then $b_A^V = \bar{b}$ is optimal, which by (C.6) yields $b_B^V = 2c - \bar{b} \geq \underline{b}$. Assuming that γ_{AB}^V wins at the price p, it holds that $p_A^V = b_A^V + p - \hat{b}(\gamma_{AB}^V) = \bar{b} + p - c$ and $p_B^V = b_B^V + p - \hat{b}(\gamma_{AB}^V) = c - \bar{b} + p$.

The developer compares two alternatives: the package bid γ_{AB}^V with realization of both projects in case of winning, and the package bid γ_{AB}^{sV} without realization of project B in case of winning. The developer's decision considers the penalty and the profit over the support period of T years. For simplicity, we do not discount future profits. In case of winning, the total profits are

$$\begin{aligned} \pi(\gamma_{AB}^V) &= 2T(p - c)\, eP\,, \\ \pi(\gamma_{AB}^{sV}) &= T(\bar{b} + p - 2c)\, eP - sP\,. \end{aligned}$$

Thus, the developer will not realize B if

$$\pi(\gamma_{AB}^V) < \pi(\gamma_{AB}^{sV}) \;\Leftrightarrow\; s < T(\bar{b} - p)\, e. \tag{C.7}$$

Then, the developer submits γ_{AB}^{sV} and uses the low bid price b_B^V only to keep the package bid price low and receive the the high price p_A^P in case of winning. If (C.7) is met, the loss-making project B will not be realized. The effect of penalties to avert losses on bidding behavior is also found in single-item auctions when the costs or values of auctioned items are uncertain (Parlane, 2003; Board, 2007; Burguet et al., 2012; Kreiss et al., 2017a).

It also follows that the developer may have an incentive to extend a one-project bid to a package bid by adding another project with no intention of realization. Consider a one-project bid γ_A^V only for A with $b_A^V = c$. If γ_A^V wins at the price p, the total profit is

$$\pi(\gamma_A^V) = T(p - c)\, eP\,.$$

Now consider the alternative bid γ_{AB}^{sV} with the same bid price c such that $\hat{b}(\gamma_{AB}^{sV}) = \hat{b}(\gamma_A^V) = c$, i.e., the auctioneer considers these two bids equal in terms of bid price. To be able to directly compare the bids γ_A^V and γ_{AB}^{sV}, we assume that their winning probabilities are also the same. (Note that in general in a CA, in which the allocation rule optimizes the sum of bids, bids with equal bid prices but different quantities may differ in their winning probability.) Then, the developer prefers γ_{AB}^{sV} over γ_A^V if

$$\pi(\gamma_A^V) < \pi(\gamma_{AB}^{sV}) \;\Leftrightarrow\; s < T(\bar{b} - c)\, e. \tag{C.8}$$

If (C.8) is met, the developer has an incentive to extend the one-project bid for A to a package bid by adding B, with no intention to realize it. Note that in both cases, the developer could additionally increase the winning probability of γ_{AB}^{sV} by further reducing b_B^V. The same problems apply in the PaB auction as well.

In the PaB auction, all package bids $\gamma_{AB}^P = ((P_A, b_A), (P_B, b_B))$ with the same average bid price $\frac{b_A^P + b_B^P}{2} = b^P \geq c$ have the same winning probability and provide the developer with the same profit in case of winning. From these bids, we choose that with $b_A^P = \bar{b}$ and $b_B^P = 2b^P - \bar{b}$.

Similar to the case of GVA, the profits of realizing both projects $\pi(\gamma_{AB}^P)$ and of realizing only project A in case of winning are

$$\begin{aligned}\pi(\gamma_{AB}^P) &= 2T(b^P - c)\, eP\,,\\ \pi(\gamma_{AB}^{sP}) &= T(\bar{b} - c)\, eP - sP\,.\end{aligned}$$

The developer prefers $\pi(\gamma_{AB}^{sP})$ over $\pi(\gamma_{AB}^P)$ if

$$\pi(\gamma_{AB}^s) > \pi(\gamma_{AB}) \;\Leftrightarrow\; s < T(\bar{b} + c - 2b^P)\, e\,. \tag{C.9}$$

Then, the developer submits γ_{AB}^{sP} and uses the low bid price b_B^P only to keep the package bid price low and receive the the high price b_A^P in case of winning. If (C.9) is met, the loss-making project B will not be realized.

The developer may also have an incentive to enter a PaB auction with an additional project with no intention of realization. Consider the one-project bid γ_A^P for A with the same bid price $b_A^P = b$, such that $\hat{b}(\gamma_{AB}^s) = \hat{b}(\gamma_A^P) = b$. In case of winning, the total profit is $\pi(\gamma_A) = T(b - c)\, eP$. Then, the developer prefers γ_{AB}^{sP} over γ_A^P if

$$\pi(\gamma_{AB}^{sP}) > \pi(\gamma_A^P) \;\Leftrightarrow\; s < T(\bar{b} - b^P)\, e\,. \tag{C.10}$$

If (C.10) is met, the developer has an incentive to extend the one-project bid for A to a package bid by adding B, with no intention to realize it.

The following example illustrates the non-realization risk.

Example 2. *The example is based on the parameters that currently apply to tenders for onshore wind projects in Germany (BNetzA, 2022b; BNetzA, 2022a): $T = 20$ years, the* *maximum bid price is* 5.88 *ct/kWh, the minimum bid price is* 0.01 *ct/kWh, and the penalty* $s = 30$ €/*kW.*

Consider a CA with PaB pricing. Let $c_A = c_B = c = 4.5$ *ct/kWh, and the annual full load hours are* 3000 *for each project. Consider the package bids* γ_{AB} *and* γ^s_{AB} *both with* $b = 4.8$ *ct/kWh. Comparing the two bids according to* (C.9)*, non-realization of project B leads to an additional expected profit of* 312 €/*kW, which is much higher than the penalty* $s = 30$ €/*kW. Therefore, the developer has a strong incentive to realize only project A in case of winning the package.*

The developer intends to realize only project A. Therefore, the developer prepares the one-project bid for A with $b_A = 4.8$ *ct/kWh and compares this with the package bid* γ^s_{AB} *that has the same bid price* $b = 4.8$ *ct/kWh. According to* (C.10)*, this leads to an additional expected profit of* 648 €/*kW, which is much higher than the penalty* $s = 30$ €/*kW. Thus, the developer has a strong incentive to submit the package bid* γ^s_{AB} *that contains B, but has no intention to realize B.*

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